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SWARMING UNMANNED AERIAL VEHICLES (UAVs): EXTENDING MARINE AVIATION GROUND TASK FORCE COMMUNICATIONS USING UAVS

by

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SWARMING UNMANNED AERIAL VEHICLES (UAVs): EXTENDING MARINE AVIATION GROUND TASK FORCE COMMUNICATIONS USING UAVS

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ABSTRACT

Technological advances and research are pushing the application of unmanned vehicles in exciting directions. This thesis emphasis is on cost estimation for a new unmanned aerial vehicle (UAV) with swarm applications. The new swarm UAV theoretical can be designed to emulate the current unmanned aerial system (UAS) mission, and expand upon the communication relay mission. Small UASs have a line-of-sight capability limitation that leaves room for improvement. The UAVs organic to the U.S. Marine Corps (USMC) are the primary focus for this analysis because organic USMC UAVs are habitually small UAVs. The analysis will determine a rough cost estimation range for a future AV with new technology. Based on the adaptation of networking topologies and research, the communication relay mission is a feasible capability to peruse in future swarm UAVs. The analysis suggests that a swarm UAV is comparable in cost to legacy UAVs currently in service in the USMC.

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LIST OF ACRONYMS AND ABBREVIATIONS

AV	aerial vehicle
BLOS	beyond line of sight
C2	command and control
CBRN	chemical biological radiological and nuclear
CER	cost estimating relationship
CMD	commercial mobile device
COP	common operating picture
COTS	commercial off-the-shelf
DOD	Department of Defense
EO	Electro optical
FAA	Federal Aviation Administration
FIST	Field Information Support Tool
FY	fiscal year
GCS	ground control station
GPS	Global Positioning System
GV	ground vehicle
HA	humanitarian assistance
HACC	Humanitarian Assistance Coordination Center
HADR	humanitarian assistance/disaster relief
HOC	humanitarian operations center
HR	humanitarian relief
IGO	inter-governmental organization
IR	infrared
ISR	intelligence, surveillance, and reconnaissance
KWH	kilowatt hour
LCCE	life cycle cost estimates
MAC	mid-air collision
MEU	Marine Expeditionary Unit
MAGTF	Marine Aviation Ground Task Force
Mil	million

NAWCAD	Naval Air Warfare Center Aircraft Division
NSA	National Security Agency
OTH	over the horizon
R&D	research and development
RF	radio frequency
SURSS	small unit remote scouting system
STUAS	small tactical unmanned aerial system
TUAS	tactical unmanned aerial system
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle
UMV	unmanned maritime vehicles
USA	United States Army
USAF	United States Air Force
USG	United States government
USMC	United State Marine Corps
USN	United States Navy
USNORTHCOM	United States Northern Command
USPACOM	United States Pacific Command
USSOCOM	United States Special Operations Command
UV	unmanned vehicle

EXECUTIVE SUMMARY

Technological advances and research are pushing the application of unmanned vehicles in exciting directions. This thesis emphasis is on cost estimation for a new unmanned aerial vehicle (UAV) with swarm applications. The new swarm UAV theoretical can be designed to emulate the current unmanned aerial system (UAS) mission, and expand upon the communication relay mission. Small UASs have a line-of-sight capability limitation that leaves room for improvement. The UAVs organic to the Marine Corps (USMC) are the primary focus for this analysis because organic USMC UAVs are habitually small UAVs. The analysis will determine a rough cost estimation range for a future AV with new technology. Based on the adaptation of networking topologies, and research the communication relay mission is a feasible capability to peruse in future swarm UAVs. The analysis suggests that a swarm UAV is comparable in cost to legacy UAVs currently in service in the USMC.

In his report on battlefield robotics, Paul Scharre (2014) of the Center for New American Security put for several recommendations to the Department of Defense (DOD). He suggested that the Office of the Secretary of Defense “undertake a study on swarming platforms to examine the potential for low-cost uninhabited systems to impose costs on adversaries” (p. 8). Analysis suggests that the cost, based on the data collected and the independent variables used, could range from \$0.33 million to \$89 million for a single AV.

Scharre also recommended that the Department of the Army and USMC “conduct a series of experiments on swarming uninhabited air vehicles for persistent surveillance, close air support, aerial resupply and communications relay to support ground maneuver forces” (2014, p 9).

This research also highlights some capabilities that exist and have been tested to allow UAVs and swarm UAVs to conduct information exchange and communications exchange.

LIST OF REFERENCES

Scharre P. (2014). *Robotics on the battlefield part II: The coming swarm.* Washington, DC: Center for a New American Security. Retrieved from http://www.cnas.org/sites/default/files/publicationspdf/CNAS_TheComingSwarm_Scharre.pdf

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I. INTRODUCTION

A. PROBLEM STATEMENT

Decreasing budgetary environments will limit the acquisition of larger unmanned aerial vehicles (UAVs) for many organizations. The long-term life-cycle cost to maintain a highly technical and large unmanned aerial system (UAS) creates a significant challenge for increasing capabilities without introducing more costs. The Department of Defense (DOD) identified UAS programs as an area with the potential to provide more value in UAS's capabilities through the leveraging of emerging technologies. The DOD has directed its' services to search out more value within their respective joint- and service- centric UAS programs. Future UAS operations require like-minded organizations to depart from the single-mission, single-payload–capable UAS to a multi-mission, multi-capable platform UAS (DOD, 2013). The relatively newly acquired RQ-21A Black Jack, Small Tactical Unmanned Aircraft System's (STUAS's) increased capabilities highlight the necessity for future UASs to capitalize on the forward momentum created by technological advances and miniaturization. When the RQ-21 is compared to its closest contemporary the RQ-7B, a stark contrast is present between the RQ-7B's nine hours of airborne endurance time and the RQ-21A's 16 hour endurance time. The RQ-7B is three times heavier than the RQ-21A and it has a quarter less speed. The Marine Corps is focused on increasing the capabilities of its small UAV fleet, which includes the RQ-7B Shadow, RQ-11 Raven, WASP, and RQ-21A, UAS programs (United States Marine Corps [USMC], 2014).

Like other organizations, the Marine Corps has a significant fleet of UAVs categorized as medium to small UASs, and this fleet continues to expand. The efficient application of new technologies and creative thinking is the key to maintaining the relevance and value of the small UAS fleet in future worldwide operations. Small UASs must increase the capabilities of the individual UAVs and ground control stations (GCSs) in the areas of beyond line of sight (BLOS) and over the horizon (OTH) communications. Merely providing intelligence surveillance and reconnaissance (ISR) as the singular capability provided by a UAV is no longer cost effective. Small UASs must provide similar capabilities to those associated with larger UASs, such as extended communications, strike, wireless networking communications, proximity avoidance, and electronic warfare.

The vision to achieving more value in the acquisitions for future UASs is outlined in two forward looking policy documents DOD (2013) and USMC (2014) discusses the utilization of advancements in UAV and UAS information sharing; multiple air vehicles (AVs) control by one ground control station (GCS), AVs controlled by mobile device, wireless communications technology embedded in AVs, and finally possessing the compulsion to incorporate the entirety of those technological characteristics into a swarm of UAVs and UASs. Those documents set specific areas to increase capability and focus effort for future UAS programs for the DOD and USMC.

B. BACKGROUND

BLOS and OTH capabilities are required to give UAV support to troops operating at extended range. The MV-22 Osprey has the ability to deliver troops to ranges that extend beyond some UASs line of sight (LOS) operating range. To support troops outside of 150-nautical mile (nm) range, UAS generally employ a hub-and-spoke method of operating. The hub-and-spoke method is characterized by one or two UASs or one or two GCSs maintaining LOS to allow a single UAV to transition between LOS connectivity from one GCS to another GCS. The transition of an AV between one GCS and another GCS is the current operating procedure employed by the larger STUAS UASs to extend operations and support range to troops on a battlefield. Hub-and-spoke operations are limited by LOS in a linear battle field or during ship-to-shore operations, due to the location of the enemy and the necessity to separations the GCS from close proximity to enemy (Department of the Army [DOA], 2006a, p.29). Larger STUAS are also called tactical unmanned aerial vehicles (TUAS). There are a clear distinctions between the STUAS and TUAS however, for simplicity, TUAS will be associated with the acronym STUAS for this thesis.

LOS and the transition required to extend AV range from launch point to the operating area is the crux of small tactical unmanned air system (STUAS) operations

(Ryan & Frater, 2001). The requirement for establishing a spoke to allow for hub-and-spoke operations is a limitation for larger STUAS's. From ship-to-shore, establishing a spoke is a costly expenditure for the following reasons: manpower, fuel, and flight time. In short, the energy costs can skyrocket to support hub-and-spoke UAV operations from ship to shore. The Marine Corps is acquiring UASs with the capability to utilize amphibious ships for landing and takeoff, and now the Marine Corps needs to extend the range of STUAS's UAVs to keep up with and support the Marine Aviation Ground Task Force (MAGTF) increased maneuverability.

While considering a means to allow STUASs to keep up with the MAGTF more question arouse. What technology is available to supplement hub-and-spoke UAV operations from ship to shore, which will decrease the energy requirement of a traditional hub-and-spoke operation employing a forward GCS? What concept or technology is available to allow airborne UAVs to act as spokes? Does the technology exist to allow STUAS UAVs to share information with each other, the customer on the ground, and the command operating center? The technology does exist in varying degrees and applications, but not as one unique set of capabilities present in a system or individual UAS or UAV. Chapter II presents a review of the literature on the singular sets of technologies and studies predominantly using commercial off-the-shelf (COTS) products to address the gap in STUAS capabilities. An example of the types of COTS AVs used are the tri-copters (examples of inexpensive UAVs) and plug-in WLAN Wi-Fi devices. Tri-copters are relatively close in size to STUASs, and Wi-Fi WLAN plug-ins are capable of supporting wireless communication networks. The MAGTF uses Marine UAS the motivation here is expand the future capabilities of UAVs to support the MAGTF.

C. MOTIVATION

The initial idea that sparked this thesis topic came from the knowledge of a communication limitation based on LOS and OTH communications. Communications retransmissions vehicles, airborne platforms, communication balloons, large UAVs, and satellite communications are all employed to mitigate LOS and OTH communication on the battlefield. The Marine Corps' fleets of UASs are categorized as STUASs, which means they have less time on station and fewer capabilities than the larger UAVs. What happens when all other aircraft assets are tasked out with higher priorities, and a Marine expeditionary unit (MEU) of 2,000 Marines, deployed on amphibious shipping, are tasked with a humanitarian mission or raid, 150–250 nm inland? The answer is the Marine Corps or Navy aviation can transport the Marines to the desired location. However, a STUAS lacks the operational distance at that range to provide support to the Marines on the ground unless STUAS GCSs are transported to the location or the amphibious ship moves close to shore. Flexibility and more innovation is the key to UASs like the STUAS increasing its supportability range past LOS and OTH limitations. At present STUAS is tied to the uplink and downlink control signal required to control the semi-autonomous AV.

The first thought to combat this limitation was to make the GCS small enough to operate on a tablet or cell phone to allow the infantryman to control it themselves. There are three issues with that idea. The first problem places the burden of operating the mobile GCS on the infantryman. The second problem is determining the transition point between the GCS and the handheld device. Operational constraints may not permit the operator of the mobile device to maintain close enough proximity to the transition point to prevent the UAV from experiencing loss link. The third problem is that placing a UAV operator in an infantry unit to operate the miniaturized mobile GCS has implications for force organization and training.

To take the burden off of infantrymen and provide them with support, the researcher of this project pictured a flying communication topology that could relay communication and video while providing updates to the infantryman as they moved throughout the battle space. The researcher was introduced to the Field Information Support Tool (FIST), which is a web-based information-sharing portal that allows individuals to share information with a network using handheld devices **(**Dush, 2014**)**.

The concepts and technology surrounding the FIST lead to the search for research and technology that could facilitate the creation of a hotspot in the sky, or a consistent and secure multi-frequency communications platform that could locate in the sky within close proximity to maneuvering forces. The desired capability would communicate with maneuver forces in non-mature communications environments to send voice and data communications through a UAV or networks of UAVs.

Large UAVs have the organic capability to utilize satellite communications to maintain communication with maneuvering forces. Most STUASs however, lack that capability. The problem of LOS still plagues STUAS GCSs and AVs limiting the communications support from STUASs. STUAS AVs must stay in close proximity to the ground unit they desire to communicate with and the GCS to utilize the inherent mobile communication need to coordinate between a ground unit and a flying vehicle. How far away from their GCS could the ground unit be to accomplish the flying hotspot or airborne communication node concept that sparked this research? The only way to answer that question is to find technology that would support long distance hotspot like communication and put it in a STUAS and test the communications distance. The hotspot concept is not a restricting idea; it is one of several technological avenues to explore in creating wireless communication networks.

Altitude, signal strength and distance are some of the most commonly known culprits for LOS complications, so LOS issues are always present. As new UAS systems are tested and researched an attempt must be made to defeat one of the three factors that cause LOS issues; the LOS issue provide the window of opportunity to test and evaluate swarm technologies' potential answer to the LOS issue. In order to start answering the LOS question from a UAV perspective, first multiple AVs must be able to relay communications from ground units to other AVs, and then those AVs need the capability to relay that communications back to GCSs. AV networks must filter information transferred between AVs to determine if the AVs can chose the appropriate communications path ways to make the appropriate communications links between ground units, command and control nodes, and UAS operators.

The final conceptual piece was introduced in the form of swarming technology. The idea came with many what-ifs, but the general concept, aside from the security implications, is almost obvious. The questions that must be answered to string a star-shaped flying communications topology across 250 nm to the infantryman are locked inside the application of swarming UAV technology. Due to endurance limitations and

LOS limitations, STUAS at first glance are prime candidates for the employment and advancements on the horizon of swarming technology. The questions that must be asked about the use of swarm technology are as follows:

1. Can UAVs participating in a swarm and share information?
2. Can UAVs participating in a swarm leave and join the swarm based on mission requirements?
3. Can UAVs retransmit controlling signals to each other to extend GCS range?
4. Can UAVs retransmit voice communication and video, and if so, what are the requirements to upgrade or purchase that capability for the STUAS fleet?
5. What is the cost estimate for swarming technology in a new UAS?

The Literature Review chapter sheds light onto most of the questions introduced in this section.

D. THESIS OVERVIEW

The introduction provides the problem statement, background, and motivation surrounding the necessity to better manage the support provided by UAS in a fiscally constrained environment. The specific lens through which this thesis explores the value of swarm technologies to the STUAS programs is through the eye of cost estimation. To provide additional information on the baseline idea and determine if swarm technology can add value to future UAS programs, comparisons must be made to connect current UAS programs with the idea of future swarm capable UAVs. Furthermore to judge if value is added, swarm technology must demonstrate the potential to increase STUAS programs capabilities and close the gap between the capabilities of small and large UASs. By surpassing or mirroring small UAS and reaching or closing the capability gap between large UASs a small UASs swarm may increase values to STUAS program. Once a link is established between swarm technologies, small UASs and large UASs, a cost estimation will provide the final comparison. This line of reasoning will add to the overall discussion of swarm technology and take a small step in advancing STUAS acquisition programs. Within this thesis several questions are addressed surrounding the feasibility of swarming technology as a communications vehicle, and the technologies potential value added to the STUAS programs.

Chapter II, Literature Review, is focused on identifying technologies that make swarming UAV technology possible and potential requirements for upgrades or capabilities in future STUAS programs to support UAV swarming capabilities.

The methodology chapter (Chapter III) outlines the cost estimation analysis, ground rules, and assumptions applied to analyze the physical and performance metrics used for the analogist and parametric cost estimation models.

Chapter IV provides a knowledge base for the UAVs in the STUAS programs and the types of networks discussed in this thesis. This chapter provides the reader with information on missions and capability to follow the comparisons between, STUASs, large UASs, and swarm technological future capabilities requirements.

Chapter V, Swarm UAV Perspective Missions, addresses the question of what type of missions and capabilities swarm UAS must have to add value to future STUAS acquisitions, and how close swarming concepts or technology is to providing capabilities similar to larger UASs. Future STUASs will need new requirements or another system added to the STUAS program if swarm technology is going to be capable of adding value.

Cost estimation and analysis are applied and reviewed in Chapter V according to the methodology set presented in Chapter III. The analogist and parametric models are based on historical, physical, and performance data to determine the best model, and to provide the best cost estimation based on the data collected.

Finally, the conclusion, Chapter VI, presents the cost estimation and the best models, and acknowledges the limitations of the models and process used. The conclusion closes with recommendations for future studies.

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II. LITERATURE REVIEW

A. NETWORKS

When researching UAV swarm technology, it is essential to address the topic of networking. Networks or networking allows multiple computers to work together for the purpose of communication exchange, information exchange, or the mutually support of a mission. UAVs can use similar network concepts to emulate the benefits computers gain from networking. Several authors have researched the topic of communication exchange between UAVs and UGVs. Kyungnho's (2013) research offers an example of a simulation used to test several algorithms. The algorithms were focused on mitigating mid-air collisions (MACs) between UAVs operating in airspace within close proximity to each other. Kyungnho's research demonstrates the results of several UAVs that successfully utilizing a mathematical model that can coordinate path following in UAVs. This model required the use of a wireless local area network (WLAN) to communicate information between UAVs.

Based on the simulation tests the UAVs were able to utilize the path generating algorithms to follow a set path, and generate a trajectory to avoid MACs (Kyungnho, 2013, pp. 10–20). The algorithm takes into account mission specific data and out puts a flight pattern for the UAVs to follow. Kyungnho (2013) explained the algorithm as follows.

> The path-generation algorithm generates a required path based on mission specifications that include the objectives to be achieved, the constraints (tactical and environment) and limitations imposed by the flight dynamics and onboard mission payload sensors. After generating a 3D flight path that accounts for mission objectives and satisfies mission and airspace constraints, the path-following capability allows a vehicle to follow a predefined path (p. 9).

The concept of pre-programming a UAV with a flight path before the start of the mission is not a new concept. However, Kyungnho's (2013) MAC avoidance research and in-flight communications between UAVs are essential. UAVs ability to react to geospatial information, which is based on algorithms, is an important aspect in identifying the existing capabilities, requirements, and technology for the advancements for swarm information exchange. Kyungnho (2013) also suggested that UAVs should have the ability to act autonomously and in concert to avoid MACs (p. 18). Kyungnho's work with algorithms supports the concept of a single UAV joining a UAV swarm and then departing the swarm as mission requirements may dictate.

What constitutes a swarm of UAVs? Is it several UAVs working in concert, UAVs with the ability to operate autonomously after they pass through air corridors, UAVs avoiding MACs? These questions help us determine what aspects of natural swarms we can or want to duplicate in a UAV swarm. Birds and flying insects rarely fly into each other, if ever. Why, because birds and insects have a presence of being instinctive to animals that swarm, therefore UAV must have a variation of MAC avoidance in their programming to duplicate the natural swarm ability. Another similarity in natural swarms that should be duplicated is division of labor between swarm members. The division of labor allows swarm members to serve the swarm in different functions. Some swarm members have wings and can fly while others crawl along the ground. Some swarm members collect the location of food while others stand ready to defend the swarm. The additions of new UVs to include unmanned ground vehicle (UGV), unmanned maritime vehicle (UMV), submerged unmanned vehicles and the variation of UAVs holds future possibility to connect these systems in a combined swarm.

This concept of air and ground UVs communicating with each other is directly derived from the interaction of ants with wings and ants without wings. Phang (2006) looked at GVs and UAVs working in support of convoy security and force protection. Phang (2006) explored a simulation model that allowed the UAV to interact with a UGV. The UGV was able to coordinate the distance a UAV flew from the UGV to maintain close proximity and carry out the assigned mission. The intent of the coordination was to pass along information in the form of optical data that could prevent the UGV from traveling into an ambush or other obstructions capable of hampering the UGV's mission (Phang, 2006). The simulations presented research that furthered the applications for interaction between unmanned air and ground vehicle. The interaction allows the GV to report Global Positioning System (GPS) information and to adjust mission characteristics based on environmental conditions or mission centric tactical changes. Increasing the amount of GVs and AVs on the ground acting in concert with each other, furthers the concept of swarm interaction. Swarm UAV interaction or at least multiple UAV communication may require wireless Wi-Fi communications.

One year after Phang's work, Mahmood (2007) established criteria for the design of a modem to support communication using UAVs. Mahmood's (2007) network operated a modem with his programming; he limited the design to account for cost, data rate transfer, simplicity of design, latency, and power consumption (2007). Mahmood used COTS equipment to minimize his cost and to emphasize the feasibility of his research for organizations with monetary constraints. Mahmood designed transmitters and receiver to support his network's low cost COTS equipment. The network was able to transmit radio frequencies (RF) and digital signals from a distance of 10 km to 100 m with a data rate modulate able range from 62 kbits to 744 kbits (Mahmood, 2007). Mahmood created a communication network designed with over-the-counter technology, supporting over-the-counter recreational UAVs that transmitted RF and digital signals up to 10 km or five nm.

B. MOBILE DEVICES AND UAVS

The Field Information Support Tool (FIST) provides a look into shared communications across multiple platforms and devices with the ability to filter and categorize incoming information as it is uploaded to the web portal. The web portal has the ability to apply restrictions and permissions to the users based on predetermined access and need-to-know parameters. The web portal also supports uploaded information from mobile devices, such as cameras, laptops, and cell phones. Information can be uploaded to the web portal from any device with permissions to access the web portal. UAV images and/or video can transmit to the web portal (Longley, 2010).

The FIST allows for continuous push and pull of communications from portal participates and has already been used for multiple missions, including: humanitarian missions, disaster relief, civil unrest environments, virus outbreaks, and intelligence gathering (Longley, 2010). The ability to utilize a similar communications structure between UAVs and UASs' participating in a swarm in some capacity is consistent with the idea of swarm technology.

C. SWARMING UAV TECHNOLOGY

The characteristics that define swarming technology need some explanation. Frantz (2005) established some guidelines that can improve understanding of the term *swarm* for this thesis and the technology. Frantz (2005) conducted simulations to test two algorithms (genetic and evolutionary) used to give the UAV swarm a pattern of behavior similar to the behavior associated with birds and insect swarms. According to Frantz (2005), "A swarm is a group of simple individuals that display characteristics such as decentralization, no synchronization, and communication amongst the group. A swarm is capable of self-organizing and completing tasks as a unit" (p. 21). Frantz's characteristics of a swarm are used as a starting point. From the starting point provide by Frantz on swarm behavior, one must also determine a swarm's ability to gather resources, attack aggressors, defend against dangers in the physical environment, and the communications vehicle for swarm integrity and information transfer.

Frantz (2005) applied the genetic and evolutionary algorithm to govern the behavior of the swarm while conducting a search mission or locating and attacking a target. Frantz's (2005) orthodox method of perceiving swarm behavior was reinforced by the behavior of ants and bees during their search for resources and while defending and attacking a threat.

Dono (2012) also looked at swarm technology using simulations focusing on the complication of takeoff and landing for UAV swarms. Dono's work simulates communication between swarm UAVs and it addresses the movement of a swarm of UAVs in positive controlled airspace, which is radar controlled airspace. The Federal Aviation Administration (FAA) is an example of an organization that controls airspace using radars. Swarm UAVs will undoubtedly come into contact with some sort of airspace controlling agency just as singular UAVs have. Swarming UAVs will interact with several different organizations as they operate over ground space and in airspace. Dono's work points out the eventuality and necessity for swarm UAVs communicate with outside agencies and for future development of swarm landing patterns or regulations. Outside of landing take off swarm UAVs may fly over cities.

Several researchers experimented with employing UAVs in a civilian urban environment. Daniel, Rhode, and Wietfeld's (2010) work suggests several agencies that a UAV network may provide value for like the police or firefighters. The types of UAVs, networks and communications those agencies might afford, are similar in scope to the UAVs, networks and communications in this thesis. Inside a urban environment UAVs have the potential to add value to police departments, fire stations, and homeland security operations using wireless mesh networks, connected to micro or small UAVs acting as sensors in concert with ground sensors to provide a mobile sensor network. (Daniel et al., 2010, pp. 179–183). Daniel et al. (2010) specifically mentions the use of swarm UAVs in a chemical biological radiological nuclear (CBRN) environment where the UAVs are able to attach CBRN equipment or air collections equipment to determine contamination or the presences of CBRN environment (Daniel et al., 2010, p. 181).

D. SUMMARY

The technology reviewed in this chapter highlights the following capabilities required to support AV swarm technology:

- Swarm UV will require programming algorithms to control autonomous or semiautonomous swarm activity using a variation of genetic, evolutionary, path generating algorithms or a variation on consistent GPS proximity interaction for autonomous or semiautonomous swarm control.

- A swarm can be autonomous or semiautonomous with a GCS that is flexible enough to be mobile or stationary and receive and share information similar to the FIST technology with application that allow for filtering and access restriction of information collected by the swarm of UVs.

- Network interaction within a swarm is wireless, using either radio frequency (RF) or Wi-Fi signals. Technology supports communication and data transfers between AVs of simple construction with COTS communication equipment. The swarm network requires communication inside the swarm between UAVs and outside the swarm to GCSs, other aircraft, and airspace control agencies.

- Swarm technology is not limited to just AVs, other UVs can participate in AV swarm interaction including GVs. Submerged UVs and UMVs are also options to consider for induction or interaction in an AV swarm. The research and development required to move swarm technology forward is consistent with the types of research and development (R&D) highlighted to further UAS integration by the Navy’s unmanned aircraft systems integration lab (Naval Air Warfare Center Aircraft Division [NAWCAD], 2012, p. 12).

III. METHODOLOGY

A. INTRODUCTION

The cost estimation of swarming UAV technology is patterned after the accepted practices associated with cost estimation guidelines established by the U. S. Government Accountability Office (GAO; 2009). The GAO's 12 characteristics of a valid estimation provides a starting point to ground this cost estimation methodology. The characteristics directly applicable to the cost estimation scope of this thesis are described in the next paragraph.

Identifying a clear task which is essential for pointed and useful cost estimation generally falls to an agent of the government. As this cost estimation is of an academic nature, the clear task is tied to the application of an analogist and parametric model of cost estimation. The intention is to draw conclusions to disregard or support assumptions based on the correlation of price to several technical aspects of a UAS or AV. Due to the limitations of this academic work and curriculum requirements, the participants of this cost estimation are limited to one. However, several individuals participated in the validation of the methods used, as is standard practice within the academic community. Furthermore, multiple usable data collection sources were used to collect data and information from program, technical, and cost data, sources including: GAO reports, DOD acquisition reports, DOD UAS focused manuals, and manufacturer websites. An assumption was made that programs acquisition documents associated with the UASs reviewed in this thesis accurately predicted the work breakdown structure, which is incorporated in the program, technical, and cost data sources used for analysis models. However, several sources used different fiscal years (FY) to record dollars; therefore, it is necessary to adhere to generally accepted normalization methods to inflate or deflate fiscal year (FY) dollars as needed. The cost estimation methodology used throughout this thesis adhered to the GAO's (2009) characteristics, when feasible for this work (p. 6).

B. GROUND RULES AND ASSUMPTIONS

This cost estimation has historical information based on previous life cycle cost estimates (LCCEs) provided by the government. The LCCEs cover unmanned aerial systems and air vehicles on a per unit cost and per system cost program basis. The type of estimation performed here is a starting point to evaluate the capability requirement uncovered in Chapter II, Literature Review, for a UAS program infused with new technology. Based on the categories for cost estimations stated by the GAO, the cost estimation used in this research is an approximation of rough order of magnitude cost estimation (GAO, 2009, p. 35). Furthermore, ground rules are required to maintain a level of understanding for the context of this cost estimation (GAO, 2009, pp. 79–80). The ground rules and assumptions of this cost estimation are not officially sponsored by the government; however, they provide a structure for integrating the most useful information into this thesis project's hypothesis and analysis.

1. Ground Rules

- Technology must exist to employ swarming UAV technology either through COTS equipment or through equipment currently present in the government's inventory. Programs under review or in the R&D phase validate the usefulness of the rough order of magnitude cost estimation.
- The cost estimate will provide an estimate for a new system cost, based on historical data.
- Cost data must apply normalization to the FY dollars and state the base year.
- Cost estimation methods used for the analysis are the analogist and parametric method.

2. Assumptions

- Weight is an analogist measurement for cost.
- Maximum endurance is an analogist measurement for cost.
- Takeoff weight is an analogist measurement for cost.

- Wingspan is an analogist measurement for cost.
- Speed is an analogist measurement for cost.
- Payload weight is an analogist measurement for cost.

C. ANALOGIST METHOD

The analogist method "subjectively compares the new system with one or more existing similar systems for which there is accurate cost and technical data" (D. Nussbaum, personal communication, June 20, 2014). A UAS with the ability to act as a swarm is the new system, which is defined in terms of design or physical parameters, performance characteristics, and known similar systems (D. Nussbaum, personal communication, June 20, 2014).

The analogy data for swarming UAVs are based on four attributes. Figure 1 depicts an example of how the analogist method is used to estimate cost.

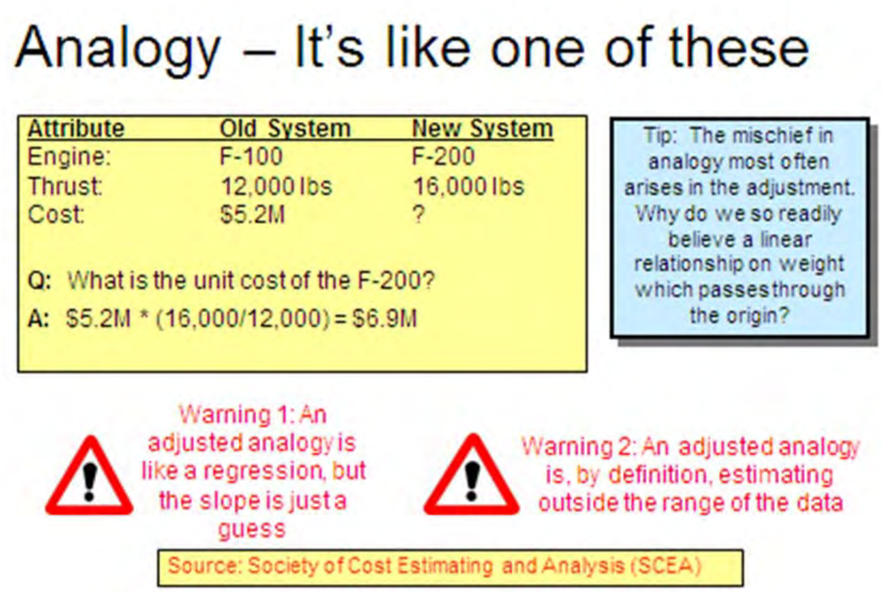


Figure 1. Analogy cost estimation example (from D. Nussbaum, personal communication, June 20, 2014).

The analogist method provides a baseline analysis to narrow the prospective independent variables used in the parametric method. The benefits of an analogist method is that it "separates development and production estimates, each based on data related specifically to development and production" (D. Nussbaum, personal communication, June 20, 2014). The historical data collected for both development and production are then compared to the new system's development and production information, a ratio is constructed, and the estimation of the future cost is generated (D. Nussbaum, personal communication, June 20, 2014).

The formula for using the analogist method is essentially the following:

$$NP = SC \times OP \tag{1}$$

Where NP = new program cost, SC = the scaling factor (new characteristic/old characteristic), and OP = the old program cost (D. Nussbaum, personal communication, June 20, 2014).

D. PARAMETRIC METHOD

The parametric method is a technique "sometimes known as the statistical method, that generates an estimate based on system performance of design characteristics. It uses multiple systems and makes statistical inferences about the cost estimating relationships" (D. Nussbaum, personal communication, June 20, 2014).

The parametric method used here is restricted to a linear regression model with one dependent variable and one or more independent variables. This enables cost estimators to draw a cost estimate based on physical and performance characteristics (D. Nussbaum, personal communication, June 20, 2014). The parametric method draws a cost estimating relationship (CER) using observable cost drivers, based on historical data.

The formula used to express the CER is shown in Equation 2. The formula depicts Y_i as the estimated cost, b_0 as the Y intercept of the line, b_1 as the slope of the regression line, X_i as the independent variable, and ε_i as the unknown random error term for the regression (D. Nussbaum, personal communication, June 20, 2014).

$$Y_i = b_0 + b_1 X_i + \varepsilon_I \quad (2)$$

Figure 2 is a flow chart that explains the rationale behind developing a linear regression model, selecting dependent variables, normalizing the data, analyzing the outcome, and drawing a conclusion.

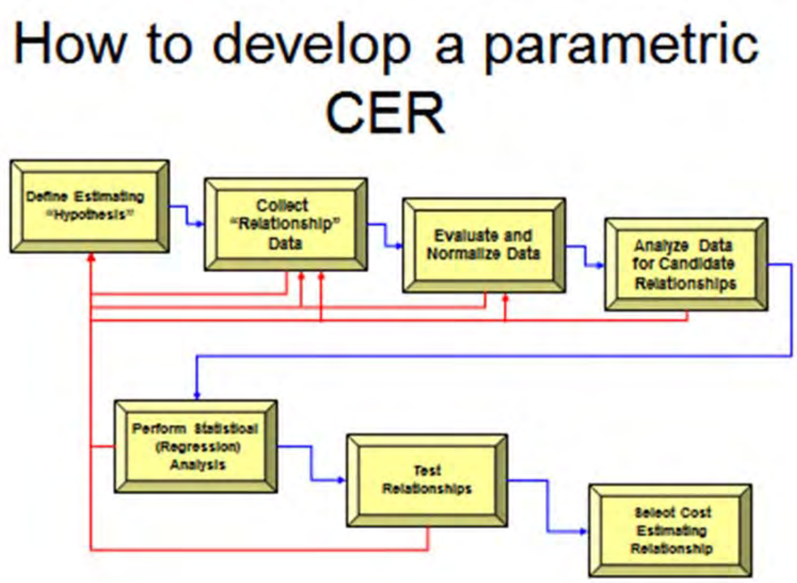


Figure 2. How to Develop a Parametric CER Selecting a Regression Model (from D. Nussbaum, personal communication, June 20, 2014).

The process of testing the relationships between the dependent variable of cost and the independent variables of physical and performance characteristics requires the selection of the best set of CERs. Testing a hypothesis surrounding a specific variable is accomplished through the use of statistics. To draw a conclusion about a specific relationship of a single dependent variable on an independent variable, a hypothesis must be tested and evaluated for significance and statistical relationships. The statistics markers that can help determine significance and relationships while employing single or multiple regression models are R^2 values, t statistics, F statistics, and the best p values (Wooldridge, 2009).

CERs are evaluated and used in cost estimation to determine the best model to use, which provides the best defendable statistical analysis given the historical information used to model physical and performance characteristics that affect cost.

The steps to determining which regression model to select as the preferred model for future cost estimation are as follows:

1. **First Conditions**

- Does the model pass the common sense test; does the regression line demonstrate the expected decrease or increase of cost based on the characteristics of the dependent variable or variables?

- Is the *F*- statistic's significance below the accepted percentage, 20 percent for this thesis?

- Is the *t*- statistic's significance (determined by the *p*- value) below the accepted percentage, 20 percent for this thesis?

2. **Second Conditions**

- Determine which regression model has the highest R^2; the regression model with the highest R^2 is the best choice.

- Evaluate the standard error between the remaining regression models; the model with the lowest standard error is the best selection for the cost estimation.

- Compute the coefficient of variation for each regression model to determine which model has the lowest variation (D. Nussbaum, personal communication, June 20, 2014).

IV. UAV AND NETWORK OVERVIEW

A. UAVS

Throughout this thesis, a line is drawn between small and large UAVs and the criteria used to make that distinction. This chapter outlines the two categories and provides photographs and informational tables to help further alleviate confusion between the two types of UAVs.

1. Small Tactical UAVs

This section provides a list of the small tactical unmanned aerial systems (STUASs) their capabilities, and the missions these UASs were designed to function in. Specific AVs highlighted in this thesis were identified in the FY 2012 budget as some of the primary weapon systems for current wars during that period (DOD, 2012, p. 9). Several other UASs were added to the thesis to increase the pool of UASs for the analytical portion of the thesis. The Wasp III, RQ-11 Raven and the RQ-20 Puma, are identified as small unit remote scouting systems (SURSSs). RQ-7B Shadow and RQ-21A Blackjack are identified as tactical unmanned aerial systems (TUASs). On average, STUASs do not possess the sufficient airborne loiter time or substantial onboard technology required to operate BLOS or OTH. Chapter I made mention of a distinction between SURSSs, TUASs and STUASs, that distinction is predominately related to size and an increased loiter time from 45 minutes to six or nine hours of airborne time for the TUAS. The RQ-7B Shadow and the RQ-21 Blackjack fall into this category. The RQ-21 Blackjack is also referred to as the RQ-21 STUAS, which may also cause some confusion. Throughout this thesis STUAS will referrer to SURSS, TUAS, RQ-21 Blackjack and all other UAVs located under the Small Tactical UAVs section in this chapter.

a. Wasp III

The mission set for the Wasp III UAS is to support squad and platoon sized reconnaissance and surveillance as an organic piece of gear assigned to that unit, similar to a radio or rifle. The environments the Wasp III is expected to operate in are "Advanced Reconnaissance and Light Infantry Military Operations on Urban Terrain (MOUT)" ("AeroVironment," 2014b). Per the manufacturer, the Wasp III's distinctive characteristics are the following: small size, durability for land or sea operations, autonomous flight and navigation, GPS, altimeter, flight range from GCS of 5 km line-of-sight, 45 minutes of endurance, 40–65 km/h speed, 2.375 ft. wing span, 1.25 ft. (38 cm) length, 0.95 lb/430 g weight (land; "AeroVironment," (b) .2014). The aerial characteristics for the Wasp III are as follows: hand launched, lands horizontally, has an operating altitude of 50–1,000 ft. above ground level (AGL), and 15–300 m AGL operating distance, and it uses the same GCS as the RQ-11 Raven and RQ-20 Puma ("AeroVironment," 2014b).

Payloads characteristics consist of an integrated forward and side look EO cameras, with the ability to swap out a high resolution EO camera with an electronic pan/tilt/zoom, and an infrared (IR) imager. This system is man-packable to support foot mobile units. Figures 3 and 4 are two variations of the Wasp AV—Figure 3 is a Wasp III, and Figure 4 is a Wasp AE.

Figure 3. Version of the Wasp, the Wasp III (from AeroVironment, 2014b).

Figure 4. Another Variant of the Wasp, the Wasp AE (from AeroVironment, 2014a).

b. RQ-11 Raven

The RQ-11 Raven runs on battery power using a single charge or rechargeable lithium battery. The AV is hand launched and recovered on its belly after it lands. In optimal conditions, the AV will belly land on a level grass or dirt surface. Optimal operational employment requires a crew of two. “The operator can launch and recover an UA in minutes from an unprepared terrain without special equipment. It can be either remotely controlled from the GCU or fly completely autonomous missions using GPS waypoint navigation” (DOA, 2006a, p. 2–10). This system is also man-packable. However, High Mobility Multipurpose Wheeled Vehicle support may be required for optimal combat space allocation.

The RQ-11 Raven can also support a payload with an electro-optical (EO)/IR sensor. The specifications and characteristics mentioned already in this section, operations of a Raven were acquired from the DOA’s UAS operations manual (2006a, pp. 2–10–2-13). Figures 5 and 6 are variations of the Raven, and Table 1 is an easy reference able table of the technical specifications of the Raven.

Figure 5. One example of a variant of the Raven (from AeroVironment, 2014d).

Figure 6. Example of another variant of Raven (from AeroVironment, 2014d).

Feature Design		*Specification*
Power		Li-Ion rechargeable battery
Wing Span		4.5 ft (1.37 m)
Weight		
	UA	4 lb (1.81 kg) (12 lb [5.44 kg] with carrying case)
	GCU	17 lb (7.71 kg)
Range		8-12 km
Airspeed		23 kt loiter, 34 kt cruise, 60 kt dash
Altitude		150-1,000 ft (45.72-304.8 m) AGL
Endurance		60 to 90 minutes (Li-Ion – rechargeable)
Payload(s)		EO/IR sensors
Launch/Recovery		Hand-launched/auto land recovery on soft, unimproved surface
Crew		Two MOS nonspecific Soldiers

Table 1. Raven specifications (from DOA, 2006a, p. 2–10).

c. *RQ-7B Shadow*

The RQ-7B Shadow has a 50 km range limited by its LOS to a single GCS. The airspeed is broken into three categories: loiter (60 knots), cruise (70 knots), and dash (105 knots). The airborne endurance is five hours, with a hydraulic rail launch system requiring 30 ft., and an arrested landing system requiring 200 ft. Current versions of the RQ-7B Shadow carry one payload capable of EO/IR sensors and laser designation. RQ-7B has three interfaces: a video receiver, a primary transceiver, and a secondary transceiver. The system is self-contained and is transported by aircraft or vehicle and trailer (DOA, 2006a, pp. 2–6–2-10). Figure 7 and Table 2 are the visual aids for the Shadow UAV.

Figure 7. Example of the Shadow's (from sUAS News, 11 April, 2012).

Feature Design	*RQ-7A*	*RQ-7B*
Wing Span	13 ft (3.97 m)	14 ft (4.27 m)
Weight	350 lb (158.76 kg)	380 lb (172..37 kg)
Range	125 km. The UA is further limited to 50 km (LOS data link) with a single GCS.	
Airspeed	70 kt loiter, 70 kt cruise, 105 kt dash.	60 kt loiter, 70 kt cruise, 105 kt dash
Altitude	15,000 ft (4,572 km) mean sea level (MSL)	
Endurance	5 hours	
Payload(s)	EO/IR sensors	
TCDL	No	Yes
Laser Designation	No	Yes in 2006
Launch/Recovery	100 m x 50 m area	

Table 2. Shadow technical specifications (from DOA, 2006a, p. 2–8).

d. RQ-20 Puma

The Puma AE is13.5-pounds, fully waterproof, hand-launched, man-portable and can be assembled in minutes. The Puma AE can be operated and recovered on sea or land by a team of two people. It requires no infrastructure, such as runways, launch pads, or recovery devices. In addition, the system is quiet and operates autonomously, providing persistent observation data (AeroVironment, 2014c). The Puma is in a phased upgrade process which will provide extended battery life, additional payload bays, more accurate navigation and GPS capability (see Figures 8 and 9).

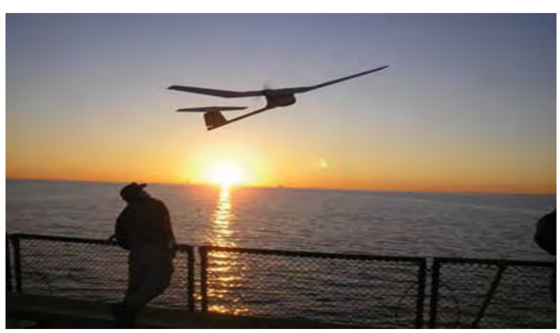


Figure 8. Puma operations at sea (from AeroVironment, 2014c).

Key Features

- All Environment - Fully Waterproof
- 3.5+ Hour Flight Endurance
- Smart Battery options to support diverse missions
- Gimbaled EO & IR Payload
- Increased Payload Capacity with optional under wing Transit Bay
- Powerful and Efficient Propulsion System
- Precision Navigation System with Secondary GPS
- Plug and Play Secondary Power Adapter
- Reinforced Fuselage for Improved Durability

Specifications

Payloads	Gimbaled payload, 360 degree continuous pan, +10 to -90 degrees tilt, stabilized EO, IR camera, and IR Illuminator all in one modular payload.
Range	15 km
Endurance	3.5+ hours
Speed	37-83 km/h, 20 to 45 knots
Operating Altitude (Typ.)	500 ft (152 m) AGL
Wing Span	9.2 ft (2.8 m)
Length	4.6 ft (1.4 m)
Weight	13.5 lbs (6.1 kg)
GCS	Common GCS with Raven, Wasp and Shrike
Launch Method	Hand-launched, rail launch (optional)
Recovery Method	Autonomous or manual deep-stall landing

Figure 9. Physical and Performance specifications of the Puma (from AeroVironment, 2014c).

e. RQ-21A Blackjack

According to Naval Air Systems Command (2014) and the United States Marine Corps' (2014) *Command Element Roadmap*, the RQ-21A Blackjack expands upon the capabilities provided by other STUASs in duration, payload, and communications capability. The increased capability allows the RQ-21A to operate from land or amphibious ship, provide night and day reconnaissance, surveillance and target acquisition, video sensors, laser range finders, and communications relay for UHF and VHF (FM). The system is self-contained and is transported by trailers and HMMWVs.

The RQ-21A Blackjack STUAS capitalized on new technology to provide the RQ-21A with significant technical characteristics; the RQ-21A Blackjack has the ability to communicate using an onboard Ethernet TCP/IP with data encryption capability, it provides up to 350 watts for payloads and is designed to accept multi-role payloads. The manufacturer reports 16 hours endurance with a ceiling greater than 19,500 ft. and a cruise speed of 60 knots and a top speed over 90 knots. Figure 10 is a photograph of the RQ-21A and Figure 11 outlines the specifications of the AV.

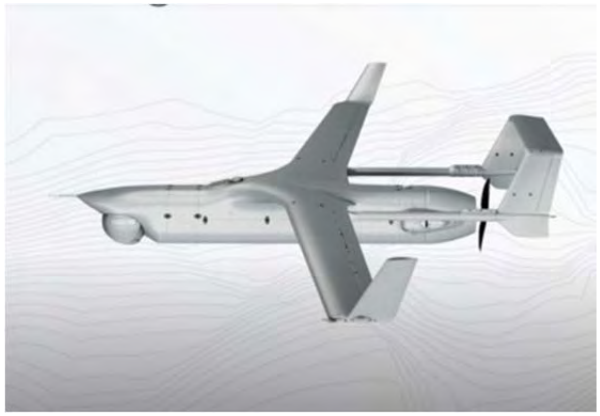


Figure 10. RQ-21A Blackjack in flight (from INSITU, 2014).

Weights

Empty structure weight: 81 lb / 36 kg › Max takeoff weight: 135 lb / 61 kg
Max payload weight*: 39 lb / 17 kg

Performance

Endurance: up to 16 hours
Ceiling: >19,500
Max horizontal speed: 90+ knots
Cruise speed: 60 knots
Engine: 8 HP reciprocating engine with EFI; JP-5, JP-8

Payload Integration

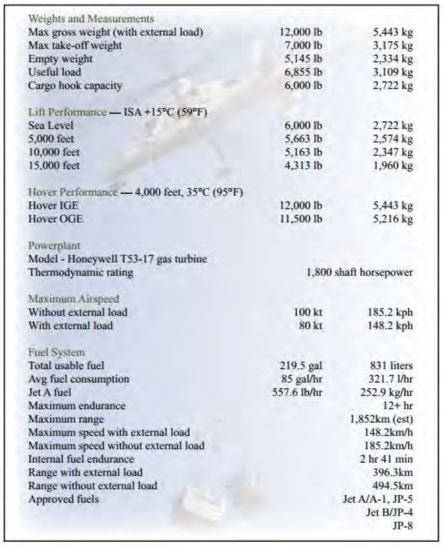
› Onboard power: 350 W for payload
› Onboard connectivity: Ethernet (TCP/IP), data encryption

Figure 11. Physical and performance specifications of the RQ-21 (from INSITU, 2014).

f. K-MAX

K-MAX UAS is capable of functioning as a traditional external lift cargo transportation helicopter with a human pilot in cockpit or as an unmanned transport cargo helicopter. Figure 12 shows the external lift nature of the K-MAX, and Figure 13 displays the characteristics and technical specifications of the K-MAX UAS (Lockheed Martin, 2010).

Figure 12. Picture of K-MAX conducting external lift (from Lockheed Martin, 2010).



Weights and Measurements		
Max gross weight (with external load)	12,000 lb	5,443 kg
Max take-off weight	7,000 lb	3,175 kg
Empty weight	5,145 lb	2,334 kg
Useful load	6,855 lb	3,109 kg
Cargo hook capacity	6,000 lb	2,722 kg
Lift Performance — ISA +15°C (59°F)		
Sea Level	6,000 lb	2,722 kg
5,000 feet	5,663 lb	2,574 kg
10,000 feet	5,163 lb	2,347 kg
15,000 feet	4,313 lb	1,960 kg
Hover Performance — 4,000 feet, 35°C (95°F)		
Hover IGE	12,000 lb	5,443 kg
Hover OGE	11,500 lb	5,216 kg
Powerplant		
Model - Honeywell T53-17 gas turbine		
Thermodynamic rating		1,800 shaft horsepower
Maximum Airspeed		
Without external load	100 kt	185.2 kph
With external load	80 kt	148.2 kph
Fuel System		
Total usable fuel	219.5 gal	831 liters
Avg fuel consumption	85 gal/hr	321.7 l/hr
Jet A fuel	557.6 lb/hr	252.9 kg/hr
Maximum endurance		12+ hr
Maximum range		1,852km (est)
Maximum speed with external load		148.2km/h
Maximum speed without external load		185.2km/h
Internal fuel endurance		2 hr 41 min
Range with external load		396.3km
Range without external load		494.5km
Approved fuels		Jet A/A-1, JP-5 Jet B/JP-4 JP-8

Figure 13. Physical and performance specifications of the K-MAX (from Lockheed Martin, 2010).

2. Larger UAVs

There are three UAVs that stand out in this chapter as large UAVs: the, MQ-1, MQ-9 and the RQ-4A. These large UAVs out weight the nearest small UAV by 500 kilo grams. The large UAVs can remain airborne well past nine hours with a speed that exceeds 100 knots.

a. *MQ-1 Predator and MQ-9 Reaper*

The MQ-1 Predator is smaller than the MQ-9; however, the MQ-9 is an upgrade of technology used in the MQ-1. The MQ-9 upgrades are based on the MQ-1 successes and increased requirement for additional munitions delivery on the battlefield. The MQ-9 has increased wing span, take-off weight, and bomb delivery capability. Both the Predator and the Reaper are 900 kilo grams heavier than the Shadow or the Blackjack. In the realm of capabilities the larger AVs have a distinct advantage in endurance, sensors, and weapons delivery capabilities. Figures 14 and Figure 15 show airborne pictures of the MQ-1 and MQ-9 UAVs respectively. See Tables 3 and 4 for the differences in performance between the two UAVs.

Figure 14. Airborne Predator (from General Atomics Aeronautical, 2014a)

Feature Design	Specification
Length	8.13 m (26 ft 8 in)
Wingspan	14.83 m (48 ft 8 in)
Height	2.21 m (7 ft 3 in)
Weight	Max: 1,020 kg (2,250 lb) Empty: 430 kg (950 lb)
Speed	Max: 217 km/h (117 kt) Cruise: 110-130 km/h (60-70 kt)
Ceiling	7,920 m (26,000 ft)
Range	740 km (400 nm)
Endurance	> 20 hours
Propulsion	Rotax 914 UL piston engine; 78.3 kW (105 hp)

Table 3. Performance Specifications for the MQ-1 Predator (from DOA, 2006a, p. 3–6).

Figure 15. Reaper is a step up in performance from the MQ-1 (from General Atomics Aeronautical, 2014b)

Feature Design	***Specification***
Length	10.97 m (36 ft)
Wingspan	20.12 m (66 ft)
Height	3.56 m (11 ft 8 in)
Weight	Max: 4,540 kg (10,000 lb) Empty: 1,380 kg (3,050 lb)
Speed	> 405 km/h (220 kt)

Table 4. Performance specification for the MQ-9 Reaper (from DOA, 2006a, p. 3–6).

b. Global Hawk

According to DOA (2006a), "The Global Hawk is the United States Air Force's (USAF's) first operational UAS in the high altitude, long endurance category. In January 1997, the Global Hawk UAS was designated RQ-4A" (p. 3–4). The Global Hawk is the largest UAV covered in this thesis. Figure 16 is the RQ-4A variation on the UAS. The Navy also has a variant of the RQ-4A with a different name and designation. Table 5 outlines the technical specifications of the RQ-4.

Figure 16. Global Hawk (from Northrop Grumman, 2014).

Feature Design	RQ-4A	RQ-4B
Length	13.53 m (44 ft 4.75 in)	14.50 m (47 ft 7 in)
Wingspan	35.42 m (116 ft 2.5 in)	39.90 m (130 ft 11 in)
Height	4.64 m (15 ft 2.5 in)	
Weight	Max: 11,600 kg (25,600 lb) Empty: 6,710 kg (14,800 lb)	
Speed	648 km/h (403 mph)	
Ceiling	19,800 m (65,000 ft)	
Range	21,720 km (11,730 nm [nautical mile])	
Endurance	36 hours	
Propulsion	Rolls-Royce/Allison F137-AD-100 turbofan	

Table 5. Performance and physical specifications of the Global Hawk (from DOA, 2006a, p. 3–4).

B. NETWORK OVERVIEW

Networks are vital to communications. Some networks use wires or fiber cables, while other networks are wireless. Network styles and their configurations are important to the sequence in which communication is passed through the network, the range of the network, and the redundancy of the network.

1. Style Configuration

The networks discussed in this section are adaptations of the networks used for computer networks. Star, ring, tree, and mesh are some of the most common designs used for network topology. When applying network topologies to swarm UAV communication and interaction, specific vocabulary is necessary. According to Cisco Systems, Inc., (2014), "The topology of a network is the arrangement or relationship of the network devices and the interconnections between them" (pp. 420–422). The two terms that require specific definition are physical topology and logical topology.

a. Physical Topology

Physical topology, unlike logical topology, is strictly based on the appearance, and of physical location and shape of the network. The following definition expresses the concept. According to Cisco Systems, Inc. (2014), "Physical topology: Refers to the physical connections and identifies how end devices and infrastructure devices such as routers, switches, and wireless access points are interconnected. Physical topologies are usually point-to-point or star" (p. 421).

b. Logical Topology

The Logical topology or the process and sequence of communications is expressed in the following quote:

> Logical topology: Refers to the way a network transfers frames from one node to the next. This arrangement consists of virtual connections between the nodes of a network. These logical signal paths are defined by data link layer protocols. The logical topology of point-to-point links is relatively simple whereas shared media offers deterministic and nondeterministic media access control methods (Cisco Systems, Inc. 2014, pp. 420–422).

c. Star

The star network configuration shown in Figure 17 shows one UAV receiving information from all other surrounding UAVs. In this configuration, it is assumed that the UAV is either acting autonomously as a hub for information exchange for the five other UAVs, or that the center UAV is acting semi-autonomously, sending information back to a GCS or a command and control device or node.

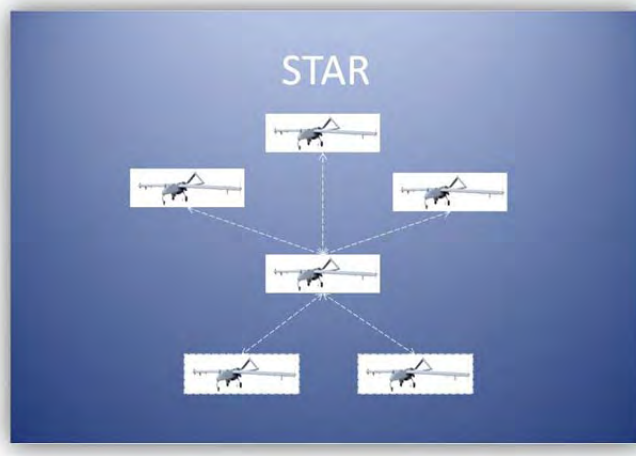


Figure 17. Star network configuration adapted for UAVs (from Cisco Systems, Inc. 2014, p. 421).

d. Ring

The ring configuration connects one AV to another AV through a point-to-point connection to another AV. The ring configuration is directly patterned off the concept of computer or device network configuration. Data and communication from the individual AVs follow the directions shown in the ring either clockwise or counter clockwise (Cisco Systems, Inc., 2014, p. 426). See Figure 18 for a graphic depiction of this configuration.

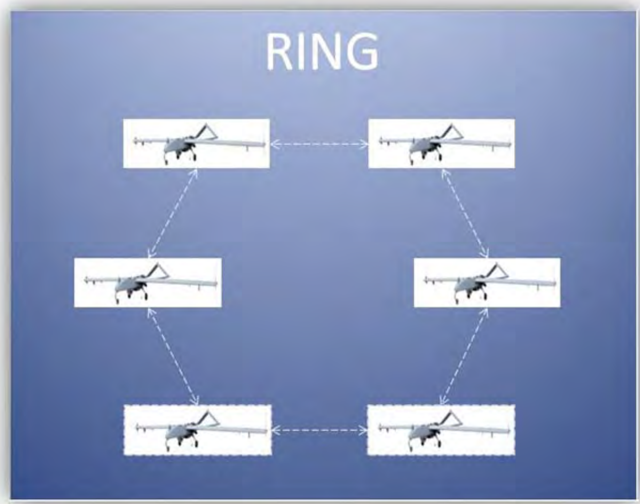


Figure 18. Ring network configuration adapted network configuration adapted for UAVs (from Cisco Systems, Inc., 2014, p. 426).

e. Tree

The tree topology is similar to a star topology with an additional AV connected to the network. When GCS or mobile devices are applied to the WAN network topology connecting the swarm, all the topologies with the exception of the mesh topology may resemble a tree topology (see Figure 19).

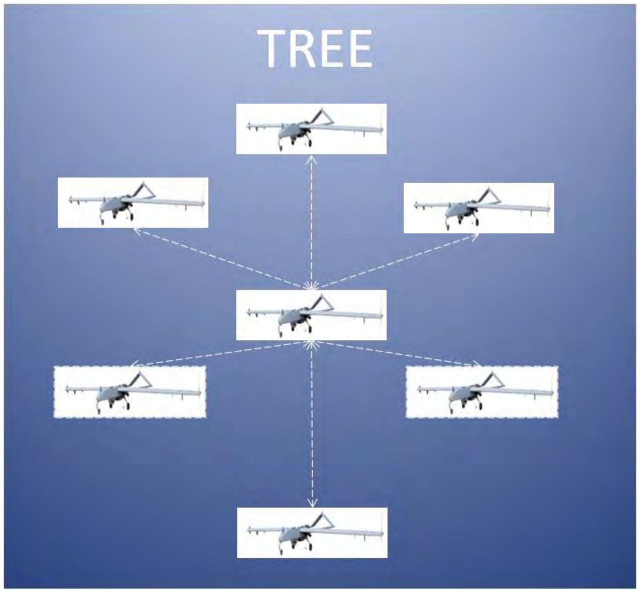


Figure 19. Tree network configuration adapted network configuration adapted for UAVs (from University of Florida, 2013, ch. 5)

f. Mesh

Looking at Figure 21, it is realistic to assume that each AV in the network is communicating with every other AV in the network. The following description expresses this concept precisely with computers as the network's focus:

> Mesh: Topology provides high availability but requires that every end system be interconnected to every other system. Therefore, the administrative and physical costs can be significant. Each link is essentially a point-to-point link to the other node. Variations of this topology include a partial mesh, where some but not all end devices are interconnected. (Cisco Systems, Inc. 2014, p. 422).

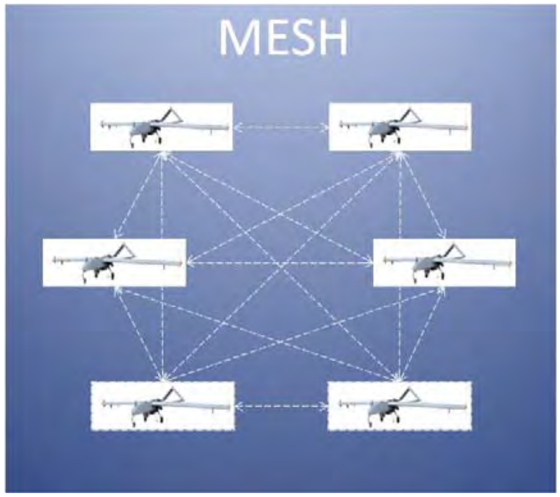


Figure 20. Mesh for UAVs (Cisco Systems, Inc. 2014, p. 422).

C. SUMMARY

UAVs come with many different capabilities and in all sizes. This chapter has provided visual references to help readers see the differences in sizes between the small UAVs and large UAVs. The physical and performance specifications listed in the tables allow for comparisons among the different characteristics associated with the UAVs presented in this chapter. The UAVs selected here are or have been tested and employed by one or more branches of the Armed Services. Speed, weight, and endurance are specific characteristics in that can affect UAV mission support. UAVs are designed to carry out specific missions.

Weight is tied to the overall size of the UAV and the type of payloads and ordnance UAVs can carry. Based on the visual aids and the performance information provided in the tables, a general assumption can be made. Heavier UAVs are associated with a longer endurance time and a faster speed. Larger, more powerful engines mean more speed. Weight and speed are trade-offs—a larger payload requires a stronger engine or larger engine to maintain a set speed requirement. Sensory, communications, onboard processing speed, and ordnance are all capabilities that are balanced by the mission requirements each individual UAV is designed to fill. Up to this point in time, UASs have not been designed to allow the smaller UAVs to communicate with each other, or to perform some of the required characteristics that constitute swarm behavior.

The Network Overview section discussed different types of networks that have the ability to communicate and organize the communication process in the network. Chapter II highlighted several experiments with COST equipment that demonstrated the ability of UAVs to function utilizing network concepts. The limitations of LOS and BLOS uplinks and downlinks for small UAVs have created an opportunity for physical topology if applied to UAVs to create an option to lower the LOS issues that small UAVs have. If those same UAVs are acting in swarm— with the ability to test signal strength to determine the best path of communication through the network, to report their locations, and to self-organize—extending communications through a network may be possible. The LOS and BLOS limitations mentioned in previous chapters necessitated hub-and-spoke operations to facilitate extended UAV operational range. Using the physical topologies as a guide, instead of a ground team, replace that team with another UAV that can pass on GCS controls, communications, in a semi-autonomous mode, or pass on GPS, and mission confirmation and pattern generation information in an autonomous mode.

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V. SWARM UAV PERSPECTIVE MISSIONS

Swarm technology can benefit military and civil missions in a multitude of ways. One report from the GAO (2008) outlined several missions that a UAS can fulfill, those missions are: communications relay, disaster recovery communications relay, maritime border protection, law and treaty enforcement, climate change observations, search, real-estate photography, pipeline survey, and infrastructure survey (pp 6–14,). The criteria applied in this chapter presents the idea that if one UAS can conduct the mission then that missions must be considered as a future swarm UAV mission. At this point in the development of swarm technology the appraisals between UAV and swarm UAV benefit is qualitative because of the lack of UAV swarms in operations. Therefore, the collection of perspective swarm missions presented in this chapter are a frame work for future testing of swarm technology benefit to UAS operations.

UASs are built to carry out specific mission requirements based on specific capability requirements. This chapter lays some of the groundwork capabilities and missions for future UAS swarm mission requirements, and by default those mission specific capabilities. The information in Figures 26–37 in the appendix and in Chapter IV contain a list of the different missions larger UAVs carry out. Large UAVs' payload size, weapons, and sensors, provide a level of support that current smaller UAVs are unable or hard-pressed to duplicate.

The difference in mission and capability between large UAVs and small UAVs is simply a result of different requirements used to acquire the desired capabilities. This thesis presents several requirements that are necessary to allow swarm UAVs to operate in mission sets comparable to larger UAVs, and also presents requirements to increase the capability of small UAVs through their participation in a UAV swarm. The resulting missions and outlined requirements applied together will add value to organizations with fleets of small UAVs.

The next section (Large UAV missions) lists the characteristics of large UAVs which are currently limited or non-existent on small UAVs.

A. LARGE UAV MISSIONS

Large UAV's current signature missions are strike, communication node, and persistent long term Intelligence reconnaissance and surveillance (ISR). Strike capability requires the ability to transport ordnance for delivery on the battlefield. Acting as a communication node often requires satellite communication capability to deal with LOS issue. Long term persistent ISR is centered on the endurance time an AV can stay on one target and observer and collect ISR data (DOA, 2006 pp 2–6─3-10). Strike, acting as a communication node and ISR are both missions and capabilities. The list has both missions and capabilities present.

Small UAVs and large UAV share some missions and capacities, those overlap are generally in ISR and situation awareness. The intersection of UAV platforms at ISR and situation awareness missions suggests that at every level of UAV operations those missions remain important. Therefore, swarms UAVs are required to duplicate that capability to serve those two missions. Additional, some of the payload capabilities overlap as well, due to the types of sensor used for the payloads. The appendix, Chapter VI and (DOA, 2006a) provide a collection of small and large UAV missions and capabilities the summation of that information is as follow:

1. Strike (mission & capability, MQ-1, MQ-9)
2. Communication node (mission & capability, RQ-21A, MQ-1, MQ-9, RQ-4A)
3. Extended duration ten hours or longer airborne flight (capability, RQ-21A, MQ-1, MQ-9, RQ-4A)
4. ISR (mission & capability, all UAVs)
5. Targeting (capability, MQ-1, MQ-9, RQ-4A)
6. Situation awareness (capability, all UAVs)
7. Advance surface to air radar (capability, RQ-4)
8. Battle management (mission and capability, RQ-4)

9. Automated identification system (AIS) (capability, RQ-21A, MQ-1, MQ-9, RQ-4A) (DOA, 2006a pp 2–6─3-10)

The next section compares some of the capability differences between small and large UAVs based on the onboard or UAS specific technology.

B. COMPARISONS

Large UAVs have communication capability that can rely on satellite communication to diminish the LOS and BLOS issues that smaller UAVs have because of their RF communications capable technology. Large UAVs do have RF communications, however, the strength of the RF signal and the increased altitude that large UAVs can fly allows for large UAVs RF use to be less affected by the three major challenges to communication (signal stringy, LOS, altitude). This makes large UAVs more capable then small UAVs on a one to one comparison, however, this comparison sets the conditions for potential value added to small UAVs when acting in a swarm with an individual dispersion of 30 nm between UAVs. If, one small UAV can communicate at a limit of 50 nm or less than three swarm UAVs should operating as communication nodes can theoretical extend that distance to a maximum of 150 nm (based on the limitations of LOS of the RQ-7A Shadow) (DOA, 2006, p. 2–8).

Next mission to be evaluated is the strike mission. A large UAV can carry several different ordnance loads an endurance of over nine hours. Small UAVs like the RQ-21A have and endurance of 16 hours, without ordnance (“INSITU.” (2014). AeroVironment website has an example of a small UAV with minimum endurance time with strike capability (switchblade UAV) (“AeroVironment,” (e). 2014). The ordnance sizes are not the same as the large UAVs and the endurance time of the small UAV is substantial less than nine hours. However, there is a small UAV with limited amount of capability with the same mission. For this reason swarm UAVs are required to have that capability.

AIS is the ability for other aircraft to identify the general location and friendly status of approaching aircraft. The RQ-21A has the ability to transmit AIS. Swarm UAVs require this capability to communicate the swarms location and status to friendly aircraft operating in the same airspace (“INSITU.” (2014). To further the application of AIS

UAVs are required to have a MAC algorithm written to prevent the swarm from flying into other aircraft and swarm members. (adapted for swarm UAVs from Kyungnho 2013, p. 18).

UAVs operated throughout the DOD are conducting individual operations outside of a swarm environment; restrictions should not be put in place to prevent a singular UAV from leaving a swarm of UAV to conduct individual operations. The flexibility is a requirement for swarm UAVs to prevent a loss in current flexibility in UAV operational environment.

C. BENEFITS

Applying the aspects of swarm activity seen in natural with insects can create a model for the variations of the UAVs employed in a swarm in the future. UAV swarm members can have primary and secondary missions similar to the mission that the small and large UAVs have now. Part of the swarm can have a primary mission of strike, act as communication nodes or, ISR. Swarm members with longer endurance time can performer the mission of battle management for the smaller UAVs. Specific UAVs can act as command and control links to other swarms or ground control stations.

Additionally, the capability to target and attack for a swarm attack or individual attack could apply for semi-autonomous or autonomous UAVs (adapted from Franz, 2005, pp. 5–36). Swarm UAV missions are as flexible and usable as the individual UAV counter parts. The addition of swarm capability creates a force multiplier for individual UAVs acting in concert with each other.

D. SUMMARY

Swarm UAVs can be designed to fill every mission current small UAVs are in support of. The GAO report out line several types of missions UAVs could support. Swarm UAVs can support those missions as well. In the large UAV section several missions where examined (strike, acting as communication nodes) other while other missions cross over between small and large UAV (ISR and situation awareness) all these mission are important to add to the requirements for future swarm UAV missions and capabilities. Size matters, the bigger the UAV the more roles or the robust type of primary mission it can serve in a swarm. Just like in nature and as currently demonstrated by the differences in the current UAV fleets, some UAVs in a swarm can have a primary mission of strike while others have a primary mission of ISR and communication node with in the swarm construct (adaptation for swarms from Phang, 2006).

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VI. COST ANALYSIS OF UAVS

A. COLLECTED DATA

The relevance of the data collected is determined by the data's ability to adhere to the ground rules, assumptions, and conditions for the analysis of the data.

1. Ground Rules

The cost estimation of swarm technology must be within the required ground rules laid out in Chapter III, Methodology. In Chapter II, technology was identified that supports the creation and interaction of swarm technology applied to UASs. The technology to test UAS intercommunication and proximity avoidance is also available. Formation flying with the use of algorithms that support genetic, evolutionary, and pattern-generating software was created and tested in UAS swarm simulations. Data transfer and RF communications between UAVs and GCSs were conducted using COTS equipment. Lastly, wireless technology is available to utilize networks with the ability to link UAVs together while airborne.

Budgetary information collected for this research came from FY2015. FY2015 was used as the base year for the AV unit cost and per system total cost of nine UASs.

2. Assumptions

Chapter III provides a list of several assumptions used to determine the realistic application of the analogist method to the cost estimation of a new swarm AV. The first assumptions suggest that the weight of a single AV or UAS is a valid metric to estimate price for a new UAS or AV. Table 6 contains the data used to create Figure 21. Based on the data collected, the trend line in Figure 21 suggests an exponential relationship between weight and price.

a. Weight Assumption

The weight assumptions use all nine of the UAVs to make a realistic determination of the relevance of weight as a cost estimation variable. Based on Table 6 and Figure 21, it appears that there is a relationship between weight and price. Therefore, the assumption is a valid variable to conduct an analysis with.

UAV	Weight kg	Per AV Price Mil
Wasp AE RQ-12A	1.30	$0.15
Puma RQ-20A	6.10	$0.33
Raven RQ-11B	1.90	$0.33
Shadow (RQ-7B 200)	209.00	$0.75
Black Jack (RQ-21A)	61.00	$0.85
Gray Eagle MQ-1C	1630.00	$5.04
Reaper (MQ-9)	4763.00	$15.83
Global Hawk (RQ-4B) Block 40	6780.00	$69.85
Triton (MQ-4C)	6780.00	$37.45

Table 6. Data used to create Figure 21

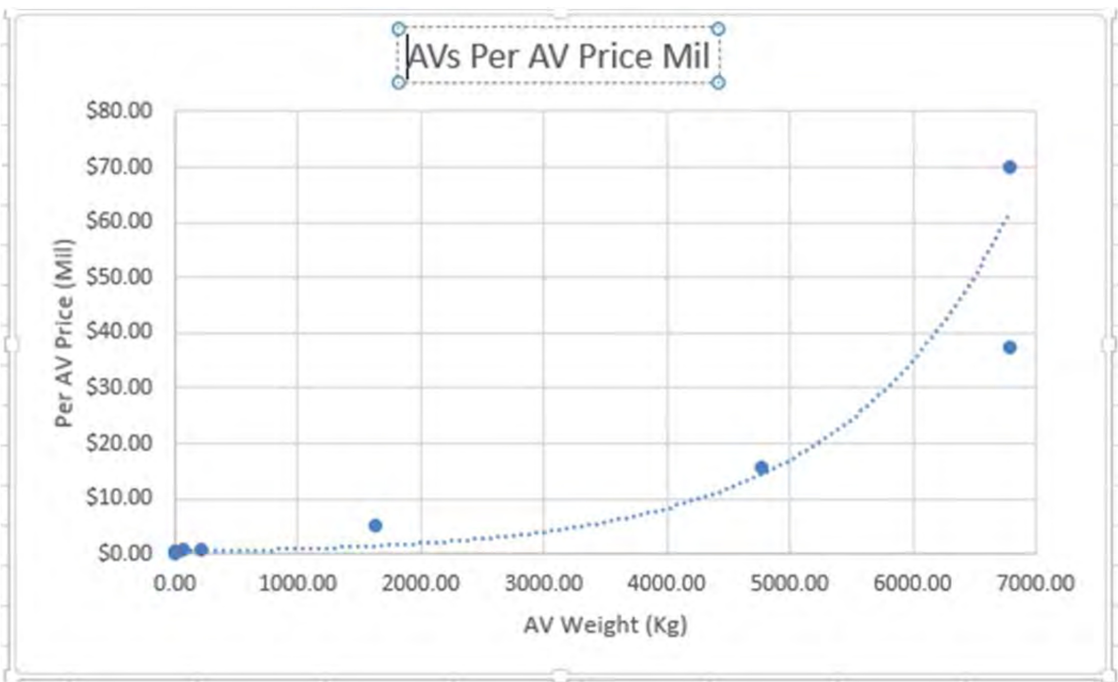


Figure 21. This figure suggests an exponential relationship between weight and price, and it supports the assumption that weight is a valid characteristic for cost estimation of an AV.

b. Endurance Assumption

Table 7 lists the data points collected and used for the graph in Figure 22 to determine whether there is a trend to suggest the characteristics of endurance as a reasonable indicator of estimating the cost of a new AV.

UAV	Endurance min	Per AV Price Mil
Wasp AE RQ-12A	50	$0.15
Puma RQ-20A	240	$0.33
Raven RQ-11B	90	$0.33
Shadow (RQ-7B 200)	540	$0.75
Black Jack (RQ-21A)	960	$0.85
Gray Eagle MQ-1C	1800	$5.04
Reaper (MQ-9)	2220	$15.83
Global Hawk (RQ-4B) Block 40	1440	$69.85
Triton (MQ-4C)	1440	$37.45

Table 7. Data from nine AVs used to generate Figure 22

Figure 22 used all nine AVs in the data set. As a result of the data points, an exponential trend line was applied to the data points. The exponential trend line suggests that the endurance assumption is a valid characteristic to estimate the future cost of a newly developed AV.

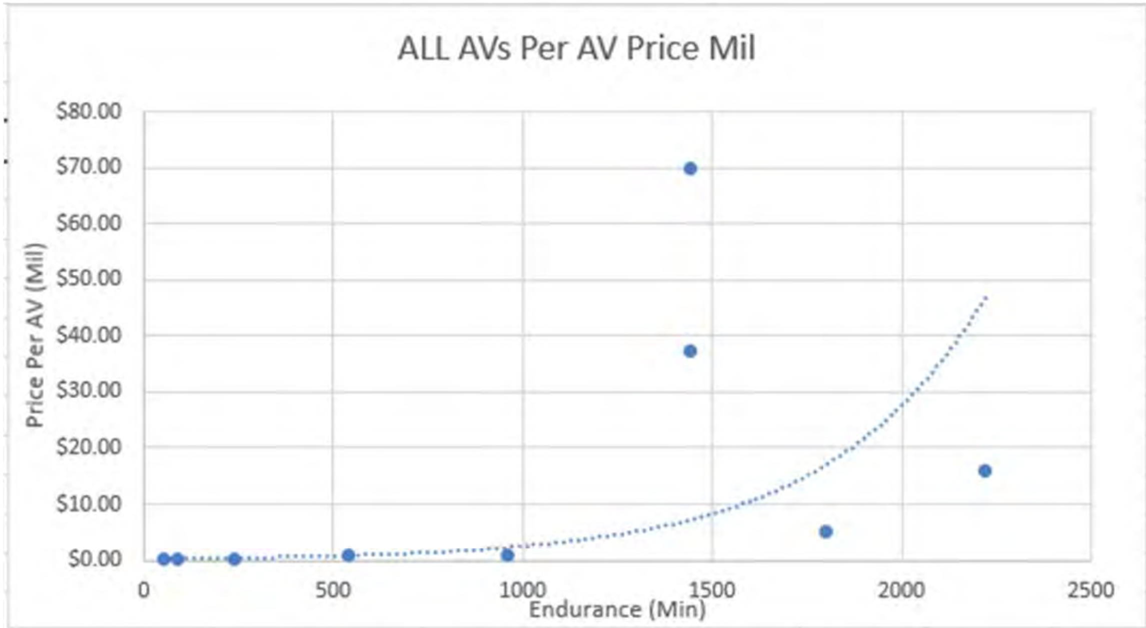


Figure 22. Endurance graph based on nine AVs with a trend line depicting exponential relationships between cost and endurance

Table 8 lists the data points for the small UAV, which were used to create the small AV per AV graph (Figure 23). The Figure 23 trend line suggests an exponential relationship between endurance and price.

UAV	Endurance min	Per AV Price Mil
Wasp AE RQ-12A	50	$0.15
Puma RQ-20A	240	$0.33
Raven RQ-11B	90	$0.33
Shadow (RQ-7B 200)	540	$0.75
Black Jack (RQ-21A)	960	$0.85

Table 8. Data Used to Create Figure 23

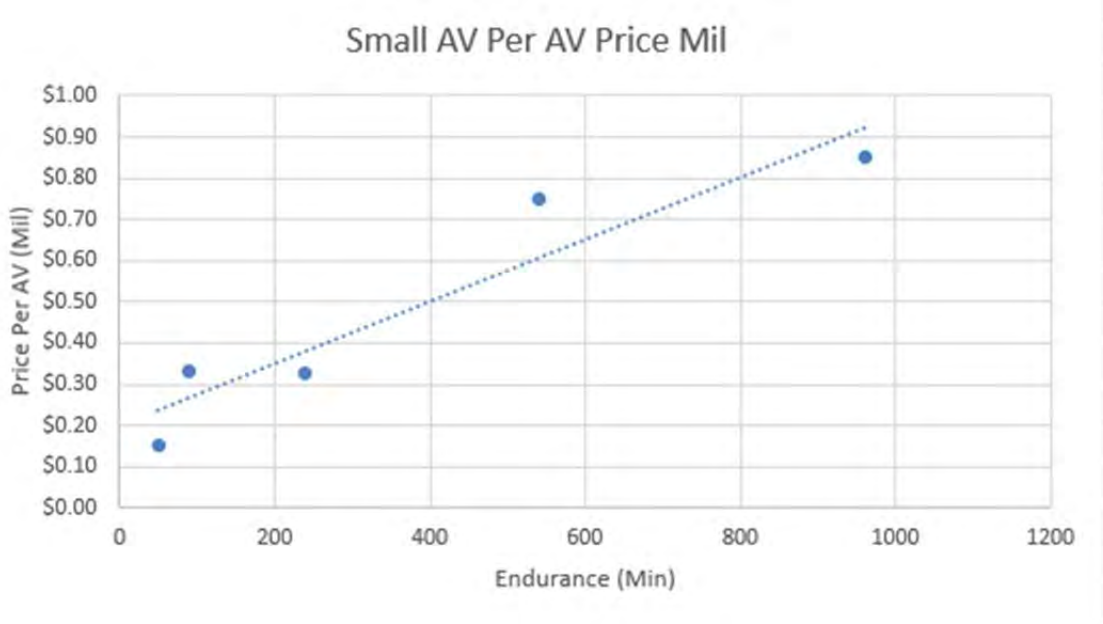


Figure 23. Endurance with a linear trend line suggesting a linear relationship between cost and endurance for small AVs.

c. *Speed Assumption*

Speed assumption is the last of the three assumptions covered in this thesis. Other cost estimation analyses may utilize three of four other characteristics or more than three characteristics. This thesis looks at only three assumptions during the analysis.

UAV	Speed knots	Per AV Price Mil
Wasp AE RQ-12A	20	$0.15
Puma RQ-20A	45	$0.33
Raven RQ-11B	44	$0.33
Shadow (RQ-7B 200)	70	$0.75
Black Jack (RQ-21A)	90	$0.85
Gray Eagle MQ-1C	130	$5.04
Reaper (MQ-9)	240	$15.83
Global Hawk (RQ-4B) Block 40	310	$69.85
Triton (MQ-4C)	310	$37.45

Table 9. Data used to generate Figure 24

Data graphed in Figure 24 and Table 10 show a relationship between speed and cost. One relationship is exponential, and the other relationship is linear, as evidenced by the trend line in Figure 24. Based on Figure 24 and Table 10, the assumption to use speed as a cost estimation technical characteristic is reasonable.

Figure 24. Graph depicting an exponential relationship between cost and speed.

UAV	Speed knots	Per AV Price Mil
Wasp AE RQ-12A	20	$0.15
Puma RQ-20A	45	$0.33
Raven RQ-11B	44	$0.33
Shadow (RQ-7B 200)	70	$0.75
Black Jack (RQ-21A)	90	$0.85

Table 10. Data used to generate Figure 25

Figure 25. This graph applies a linear trend line to the data which suggest a linear relationship between cost and speed.

B. ANALYSIS

Weight, endurance, and speed are all acceptable variables with which to conduct an analysis, based on the relationships displayed in the tables and figures presented in this chapter up to this point. Those relationships suggest a linear and exponential relationship between the variables and price.

1. Analogist

The first model used in this research is the analogist model. It is used to analyze price and weight for nine UASs based on the first assumption listed in Chapter III. Figure 25 presents the collection of data used to generate the analogist model. Table 11 presents the averages for the characteristics used in the model to present a rough starting point for a singular AV using all the AV data for the nine types of AVs—the small AVs and the large AVs.

UAV	Weight kg	Speed knots	Endurance min	Per AV Price Mil	Year	QTY
Wasp AE RQ-12A	1.30	20	50	$0.15	2015	1
Puma RQ-20A	6.10	45	240	$0.33	2015	1
Raven RQ-11B	1.90	44	90	$0.33	2015	1
Shadow (RQ-7B 200)	209.00	70	540	$0.75	2011	1
Black Jack (RQ-21A)	61.00	90	960	$0.85	2015	1
Gray Eagle MQ-1C	1630.00	130	1800	$5.04	2015	1
Reaper (MQ-9)	4763.00	240	2220	$15.83	2015	1
Global Hawk (RQ-4B) Block 40	6780.00	310	1440	$69.85	2015	1
Triton (MQ-4C)	6780.00	310	1440	$37.45	2015	1

Table 11. UAS Information Collected for a Single AV (after Barr Group Aerospace, 2014).

Based on the information collected in Figure 23, the average weight, speed, endurance, and AV per unit cost represents a rough estimate of the AV price for a single AV with swarm technology. Avg All AVs of $14.51 million is the rough estimate of one AV using all nine UAVs based on the information collected. This single AV average characteristics consist of 2248.03 kg, 139.89 knots speed, and 975.56 minutes of endurance. The rough characteristics of a single AV based on the small UAV information is 55.86 kg, 53.80 knot speed, 376 minutes of endurance, and a per unit cost of $0.48 million dollars. The characteristics of a large AV are out of the focus for this thesis for adding benefit to the STUAS category of UAS (see Table 12).

Avg All AVs	2248.03	139.89	975.56	$14.51
Avg Small AVs	55.86	53.80	376.00	$0.48
Avg Large AVs	4988.25	247.50	1725.00	$32.04

Table 12. Average characteristics and price for a new AV with swarm technology.

a. Weight Analogist Analysis

Based on the formula for estimating new unit cost (see Figure 1 in Chapter III), the new system’s weight is divided by the old system’s weight, and the quotient of that function is multiplied by the old system’s per AV price to estimate the new unit cost. Table 13 displays the new unit prices for a new AV with a weight of 55.86 kg. Table 14 shows the same information for a new AV with a new weight of 2,889.27 kg, and for Table 15, the new weight is 4,988.25 kg.

	New System Weight (Kg)	Attribute (Old Sys)	Old System	New Unit Cost
Avg Weight Small AVs (Kg)	55.86	Weight (Kg)	Per AV Price (Mil)	NP Swarm AV (Mil)
Swarm AV (1)		1.30	$0.15	$6.45
Swarm AV (2)		6.10	$0.33	$3.01
Swarm AV (3)		1.90	$0.33	$9.79
Swarm AV (4)		209.00	$0.75	$0.20
Swarm AV (5)		61.00	$0.85	$0.78
Swarm AV (6)		1630.00	$5.04	$0.17
Swarm AV (7)		4763.00	$15.83	$0.19
Swarm AV (8)		6780.00	$69.85	$0.58
Swarm AV (9)		6780.00	$37.45	$0.31

Table 13. New weight for the new AV is 55.86 kg).

Figure 24 shows the cost of AVs increasing as weight increases for small AVs, and the cost decreasing for large AVs as the weight variable decreases. The next two tables, Tables 14 and 15, show an increase in the weight variable for the new AV resulting in a drastic increase of price for the small AVs. Conversely, the large AVs' cost decreases because of the decrease in the weight variable based on the increased numerator.

Avg Weight Large AVs (Kg)	New System Weight (Kg)	Attribute (Old Sys)	Old System	New Unit Cost
All Swarm Av	2889.27	Weight (Kg)	Per AV Price (Mil)	NP Swarm AV (Mil)
Swarm AV (1)		1.30	$0.15	$333.38
Swarm AV (2)		6.10	$0.33	$155.83
Swarm AV (3)		1.90	$0.33	$506.38
Swarm AV (4)		209.00	$0.75	$10.37
Swarm AV (5)		61.00	$0.85	$40.31
Swarm AV (6)		1630.00	$5.04	$8.92
Swarm AV (7)		4763.00	$15.83	$9.60
Swarm AV (8)		6780.00	$69.85	$29.77
Swarm AV (9)		6780.00	$37.45	$15.96

Table 14. New weight for the new AV is 2889.27 kg)

	New System Weight (Kg)	Attribute (Old Sys)	Old System	New Unit Cost
Avg Weight All AVs (Kg)	4988.25	Weight (Kg)	Per AV Price (Mil)	NP Swarm AV (Mil)
Swarm AV (1)		1.30	$0.15	$575.57
Swarm AV (2)		6.10	$0.33	$269.04
Swarm AV (3)		1.90	$0.33	$874.26
Swarm AV (4)		209.00	$0.75	$17.90
Swarm AV (5)		61.00	$0.85	$69.59
Swarm AV (6)		1630.00	$5.04	$15.41
Swarm AV (7)		4763.00	$15.83	$16.58
Swarm AV (8)		6780.00	$69.85	$51.39
Swarm AV (9)		6780.00	$37.45	$27.55

Table 15. New weight for the new AV (4,988.25 kg)

Tables 13, 14, and 15 supports the assumption that as weight increases, cost increases per AV, and as weight decreases, cost decreases per AV. Based on the data presented, the average weight of the small AVs, 55.86 kg, results in the lowest new swarm per AV cost.

b. *Endurance Analogist Analysis*

This section has three tables that apply the analogist analysis to the data collected—Tables 16, 17, and 18. Table 16 uses the average endurance of the smaller UAVs as the new system variable, while Tables 17 and 18 use all nine UAVs' average endurance and the larger UAVs' average endurance.

	New System Endurance (Min)	Attribute (Old Sys)	Old System	New Unit Cost
Avg Endurance Small AVs (Min)	376	Endurance (Min)	Per AV Price (Mil)	NP Swarm AV (Mil)
Swarm AV (1)		50	0.15	1.128
Swarm AV (2)		240	0.329	0.515
Swarm AV (3)		90	0.333	1.391
Swarm AV (4)		540	0.75	0.522
Swarm AV (5)		960	0.851	0.333
Swarm AV (6)		1800	5.035	1.052
Swarm AV (7)		2220	15.83	2.681
Swarm AV (8)		1440	69.848	18.238
Swarm AV (9)		1440	37.445	9.777

Table 16. Endurance Attribute based on the Average Endurance for the Small AVs

	New System Endurance (Min)	Attribute (Old Sys)	Old System	New Unit Cost
Avg Endurance All AVs (Min)	976	Endurance (Min)	Per AV Price (Mil)	NP Swarm AV (Mil)
Swarm AV (1)		50	0.15	2.927
Swarm AV (2)		240	0.329	1.337
Swarm AV (3)		90	0.333	3.610
Swarm AV (4)		540	0.75	1.355
Swarm AV (5)		960	0.851	0.865
Swarm AV (6)		1800	5.035	2.729
Swarm AV (7)		2220	15.83	6.956
Swarm AV (8)		1440	69.848	47.320
Swarm AV (9)		1440	37.445	25.368

Table 17. Endurance attribute based on the average endurance for all nine AVs.

Avg Endurance Large AVs (Min)	New System Endurance (Min)	Attribute (Old Sys)	Old System	New Unit Cost
All Swarm Av	1725	Endurance (Min)	Per AV Price (Mil)	NP Swarm AV (Mil)
Swarm AV (1)		50	0.15	5.175
Swarm AV (2)		240	0.329	2.365
Swarm AV (3)		90	0.333	6.383
Swarm AV (4)		540	0.75	2.396
Swarm AV (5)		960	0.851	1.529
Swarm AV (6)		1800	5.035	4.825
Swarm AV (7)		2220	15.83	12.300
Swarm AV (8)		1440	69.848	83.672
Swarm AV (9)		1440	37.445	44.856

Table 18. Endurance attribute based on the average endurance for the large AVs.

The analysis for endurance has returned a per AV price that ranges from $0.33 million to $83.672 million. The analogist model suggests that swarm UAVs are comparable to the cost of individual UAVS without the added technology.

c. Speed Analogist Analysis

Tables 19, 20, and 21 use the averages for speed for the small UAVs, all nine UAVs, and the large UAVS as the new system variable to model the future price of a swarm AV.

	New System Speed knots	Attribute (Old Sys)	Old System	New Unit Cost
Avg Speed Small AVs knots	53.8	Speed knots	Per AV Price (Mil)	NP Swarm AV (Mil)
Swarm AV (1)		20	0.15	0.4035
Swarm AV (2)		45	0.329	0.393
Swarm AV (3)		44	0.333	0.407
Swarm AV (4)		70	0.75	0.576
Swarm AV (5)		90	0.851	0.509
Swarm AV (6)		130	5.035	2.084
Swarm AV (7)		240	15.83	3.549
Swarm AV (8)		310	69.848	12.122
Swarm AV (9)		310	37.445	6.499

Table 19. Speed attribute based on the average speed for the small AVs

	New System Speed knots	Attribute (Old Sys)	Old System	New Unit Cost
Avg Speed All AVs knots	139.89	Speed knots	Per AV Price (Mil)	NP Swarm AV (Mil)
Swarm AV (1)		20	0.15	1.049
Swarm AV (2)		45	0.329	1.023
Swarm AV (3)		44	0.333	1.059
Swarm AV (4)		70	0.75	1.499
Swarm AV (5)		90	0.851	1.323
Swarm AV (6)		130	5.035	5.418
Swarm AV (7)		240	15.83	9.227
Swarm AV (8)		310	69.848	31.519
Swarm AV (9)		310	37.445	16.897

Table 20. Speed attribute based on the average speed for all nine AVs

Avg Speed Large AVs knots	New System Speed knots	Attribute (Old Sys)	Old System	New Unit Cost
All Swarm Av	247.5	Speed knots	Per AV Price (Mil)	NP Swarm AV (Mil)
Swarm AV (1)		20	0.15	1.856
Swarm AV (2)		45	0.329	1.810
Swarm AV (3)		44	0.333	1.873
Swarm AV (4)		70	0.75	2.652
Swarm AV (5)		90	0.851	2.340
Swarm AV (6)		130	5.035	9.586
Swarm AV (7)		240	15.83	16.325
Swarm AV (8)		310	69.848	55.766
Swarm AV (9)		310	37.445	29.896

Table 21. Speed attribute based on the average speed of the large AVs

2. Parametric

The parametric approach requires cost estimating relationships (CERs) to be provided to create cost estimating variables. For this parametric analysis, weight, endurance, and speed are the cost drivers that were identified in the assumptions section and tested in the analogist section to determine whether a relationship did exist. Weight, endurance, and speed are the CER variables that were used in this parametric approach.

a. Linear Regression Model for Weight

The linear regression model below was created using the data collected for nine AVs' weights and prices. The model regression returns are found in Table 22–24. The results shown in Tables 22 and 23 pass the first conditions requiring an *F*-statistic and *t*-test *p*-value of less than 20%.

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3730.977684	3730.977684	27.99075961	0.001134859
Residual	7	933.0523411	133.2931916		
Total	8	4664.030025			

Table 22. *F*-statistic value for weight is less than 20 percent.

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-1.692204735	4.917968516	-0.344086126	0.740886362	-13.32135236	9.936942887	-13.32135236	9.936942887
Weight kg	0.00720634	0.001362095	5.290629416	0.001134859	0.003985497	0.010427184	0.003985497	0.010427184

Table 23. The *p*-value for the weight coefficient is less than 20 percent.

The second condition requires a selection of the best model, which is the model with the highest R^2 after the first condition is passed (see Table 24). In addition, the model with the lowest standard error represents the model with the lowest unexplained variables present in the model.

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.894397665
R Square	0.799947184
Adjusted R Square	0.77136821
Standard Error	11.54526706
Observations	9

Table 24. R^2 value for weight is the highest in the weight model.

b. Linear Regression Model for Endurance

The endurance model in Table 25 passes the less-than-20 percent standard for the model's F-statistic. However, Table 26 shows the t-test was a failure because the p-value for the model failed the less-than-20 percent criteria for acceptable models.

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1049.45108	1049.451	2.032368825	0.197011282
Residual	7	3614.578945	516.3684		
Total	8	4664.030025			

Table 25. F-statistic value is less than 20 percent.

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.418923811	12.45162744	0.033644	0.974100201	-29.02449642	29.86234404	-29.02449642	29.86234404
Endurance min	0.014441992	0.010130382	1.425612	0.197011282	-0.009512556	0.038396539	-0.009512556	0.038396539

Table 26. The t-test for the coefficient for the endurance independent variable fails the p-value test.

The endurance model has the lowest R^2 and the highest standard error for all three models (see Table 27). First conditions were not met for the endurance model because the p-value was high. If the data had resulted in the first conditions being met, the second conditions would still result in the endurance model being the worst case model for single independent variable models for cost estimation.

Regression Statistics	
Multiple R	0.474351666
R Square	0.225009503
Adjusted R Square	0.114296575
Standard Error	22.72374134
Observations	9

Table 27. R^2 for the endurance model has the lowest value

c. Linear Regression Model for Speed

The linear regression model's output is represented in Tables 28, 29, and 30. The results of the model, based on the metric used to determine the acceptability of the model, show that the speed model passes the conditions laid out in the methodology chapter. The speed model is valid for cost estimation based on the thesis parameters.

ANOVA					
	df	SS	MS	F	Significance F
Regression	1	3562.869993	3562.869993	22.64892407	0.002061642
Residual	7	1101.160032	157.308576		
Total	8	4664.030025			

Table 28. F-Statistic for the significance of the model is less than 20 percent.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-10.90711692	6.782155701	-1.60820798	0.151824984	-26.94436677	5.130132927	-26.94436677	5.130132927
Speed knots	0.181679946	0.038175366	4.759088575	0.002061642	0.091409551	0.271950342	0.091409551	0.271950342

Table 29. t-test based on the p-value for the coefficient is less than 20 percent.

Regression Statistics	
Multiple R	0.874015871
R Square	0.763903743
Adjusted R Square	0.730175706
Standard Error	12.54227156
Observations	9

Table 30. The R^2 term 76.39 percent.

d. Multi Linear Regression Models

The multi linear regression model uses two or more of the independent variables to determine the best model for the estimation of a new swarm AV. The metric to determine the best model is outlined in Chapter III. The best model for the estimation is the model that passes the *F*-statistic, passes the *t*-test with a *p*-value of less than 20%, has the highest R^2, and has the lowest standard error value.

There were four models used to identify the best estimation model: weight and speed (Table 31); weight and endurance (Table 32); endurance and speed (Table 33); and weight, endurance, and speed (Table 34). All models passed the *F*-statistic test suggesting that the model is better than a general average (see Tables 31 and 32).

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3745.212674	1872.606337	12.228369	0.007645
Residual	6	918.817351	153.136225		
Total	8	4664.030025			

Table 31. Weight and speed *F*-statistic test

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3968.528748	1984.264374	17.117993	0.003316
Residual	6	695.501277	115.916879		
Total	8	4664.030025			

Table 32. Weight and endurance *F*-statistic test

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	4045.704126	2022.852063	19.628989	0.002330
Residual	6	618.325899	103.054316		
Total	8	4664.030025			

Table 33. Endurance and speed *F*-statistic test

ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	4047.668106	1349.222702	10.945052	0.012306
Residual	5	616.361919	123.272384		
Total	8	4664.030025			

Table 34. Weight, endurance, and speed *F*-statistic test

While all four models passed the *F*-statistic test, only two models passed the *t*-test, which required a *p*-value less than 20 percent. The two models that passed the *t*-test were weight and endurance and endurance and speed (see Tables 35 and 36).

	Coefficients	*Standard Error*	*t-Stat*	*p-Value*
Intercept	3.702165	5.935728	0.623709	0.555773
Weight kg	0.009032	0.001800	5.018218	0.002408
Endurance min	-0.009736	0.006801	-1.431545	0.202236

Table 35. Weight and endurance *t*-test with a *p*-value less than 20%

	Coefficients	*Standard Error*	*t-Stat*	*p-Value*
Intercept	-7.260797	5.742060	-1.264493	0.252950
Speed knots	0.263767	0.048917	5.392078	0.001676
Endurance min	-0.015508	0.007165	-2.164541	0.073614

Table 36. Endurance and speed *t*-test with a *p*-value less than 20%

The final metrics used to determine which model to use to estimate the cost of a swarm UAV were the R^2 value and the model with the lost error term. Tables 37 and 38 show that the endurance and speed model is the best model to use given the data collected.

Regression Statistics	
Multiple R	0.922431
R Square	0.850880
Adjusted R Square	0.801173
Standard Error	10.766470
Observations	9.000000

Table 37. Weight and endurance R^2 is lower in this table than Table 38 and the standard error is higher.

Regression Statistics	
Multiple R	0.931357
R Square	0.867427
Adjusted R Square	0.823236
Standard Error	10.151567
Observations	9.000000

Table 38. Endurance and speed model is the best model to use based on the data and the metrics applied.

e. The Price of a Swarm AV Based on the Models Used

The average characteristic of a new swarm AV based on the data is as follows: weight consists of 2,248.03 kg, 139.89 knots speed, and 975.56 minutes of endurance. That size of AV is grossly larger than the largest of the small AVs. To a more realistic characteristic of weight to the analogist model the applied the average weight of the small AVs as a more realistic variable. The price based on weight for AVs ranges from $0.31 million to $6.45 million. To increase the endurance of the AV based on the average of all nine AVs, the price ranges from $0.86 million to $47.3 million. However, when the average endurance of the small AVs was applied to the model, the price ranged from $0.33 million to $18.2 million. The final model determined the price of a swarm AV based on speed. That model returned a price between $0.39 and $31.5 million based on the highest cost estimate using all nine AVs' speed average, and the lowest cost based on the small AVs' speed average.

Using parametric-based models, the linear regression analysis points to the weight model as the best cost estimate tool to determine the cost of a new swarm AV. That formula is shown in Table 39 along with the price. The linear regression model suggests that as the weight of the AV decreases from the AV weight of the nine AVs in the data, the cost estimation for a swarm AV will decrease (see Table 39).

Linear Regression Model		Future Weights (kg) Estimate	Price per AV (Mil)
Y =	Price (Mil)	2249	$14.515
x =	Weight (kg)	1000	$5.514
b =	Intercept	500	$1.911
		250	$0.109
x =	0.00720634	125	-$0.791
b =	-1.692204735	75	-$1.152
Y= b + x	Formula		

Table 39. Multi Linear Regression Model using the average weight of the AVs suggesting a decrease in estimated cost based on weight

The best multi linear regression model based on the data and the metrics applied is the endurance and speed model. That formula is shown in Table 40 along with the price.

Multi Linear Regression Model		Future Speed Estimates	Future Endurance Estimates	Price per AV (Mil)
Y =	Price (Mil)	139.89	975.56	$21.509
x =	Endurance (Min)	129	875	$20.196
x1 =	Speed knots	119	775	$19.109
b =	Intercept	109	675	$18.022
		99	575	$16.935
x =	-0.015508	89	475	$15.848
x1 =	0.263767			
b =	-0.260797			
Y= b + x+ x1	Formula			

Table 40. Multi linear regression model starting with the average using all nine AVs then decreasing speed and endurance closer to the capabilities of the small AVs.

C. SUMMARY

The analogist model provides a high and low price for a swarm AV based on how closely the swarm AVs are to the endurance and speed of the larger AVs, as well as the more realistic comparison and close of the swarm AVs to the smaller AVs. As the AVs move closer to the size and individual capabilities of the large AVs, the cost estimate is around $89 million. The estimate suggests that as the swarm AVs remain closer in weight, endurance, and speed to the smaller AVs, on average the price estimation is as low as $0.33 million.

The single linear regression model and the multi linear regression model both suggest that the analogist price of $89 million for a new swarm AV is likely an extreme estimate of the cost of a new swarm AV. However, as multiple AVs are purchased for the new UAS swarm, the price will approach or exceed $89 million for the entire system and additional AVs. The multi linear regression model suggests that the price of 10 swarm AVs with a speed of 89 knots and 475 min of endurance is estimated to cost $158.48 million, and the linear regression model suggests that 10 swarm AVs with a weight of 250 kg is estimated to cost $1.09 million.

VII. CONCLUSION

A. TECHNOLOGY REVIEWED

The technology reviewed in Chapter II outlined some of the requirements needed to support AV swarm technology. New algorithms must be programmed for AVs to be controlled autonomously or semi-autonomously. Some of the new algorithms have been tested, and others already exist as part of landing sequences or in larger AVs. Swarm activities for UAVs are a variation of genetic, evolutionary, and path-generating algorithms which also require consistent GPS proximity interaction between swarm members in either an autonomous or semi-autonomous mode.

Flexibility is another aspect that must be maintained as AVs interact with UAV swarms. There should be flexibility in the manner of control of an AV and a UAV swarm. Technology is available that allows GCSs or mobile devices to control semi-autonomous AVs. This flexibility should remain to allow GCSs or mobile devices to receive and send communication or information to autonomous UAV swarms. FIST technology provides a framework to consider for future information collection and dispersion throughout a network, with the ability to filter and restrict access to information.

Network interaction within a swarm is wireless by default, either using RF or Wi-Fi signals. Technology supports communication and data transfers between AVs of simple construction with COTS communication equipment. The swarm network requires communication inside the swarm between UAVs and outside the swarm to GCSs, other aircraft, and airspace control agencies.

Swarm technology is not limited to just AVs; there are a wealth of opportunities for subsurface, above ground, and above surface UVs to act in swarms. All UVs in a swarm do not need to be restricted to the same primary mission. Just like in nature, some members of the swarm are workers, gatherers, or fighters, while others relay messages. UAVs can have primary and secondary missions to perform while acting in a swarm.

B. METHODOLOGY REVIEWED

The methodology used for this thesis project was based on an approximation of a rough order of magnitude cost estimation to determine the range of cost for a new UAV with swarm technology. Ground rules were set to cage the analysis. Technology does exist to employ swarm UAV technology, and experiments have been conducted using COTS equipment. The cost data collected was in FY2015 dollars, and the independent variables were normalized by a measurement of weight (kg), speed (knots), and endurance (min). Finally, four models were used to find a range for the future cost of the new swarm UAV. The average of all UAVs based on the characteristics was the initial model, followed by an analogist model and a parametric model consisting of both single linear regression and multi linear regression.

The assumptions were tested to determine the reality of using weight, endurance, and speed. Ideally, more than three characteristics would be included in the model; however, time was a constraint for this rough estimate.

C. UAVS AND NETWORKS

Future swarm UAVs will be designed to carry out specific missions in a primary or secondary capacity. Those future missions will be affected by the design of the UAV based on performance and technical characteristics (such as speed, weight, and endurance). Sensory, communications, onboard processing speed, and ordnance are all capabilities that are balanced by the mission requirements for each individual UAV. When we add swarming capability as a flexibility to individual UAVs and not as a single mission capability, the potential for upgrading a current fleet of small UAVs is available, as well as the potential of building new UAVs with the ability to swarm or act individually.

In order to organize a swarm, physical topology will be applied to a swarm. The names presented in this thesis were an adaptation of network topologies; however, there are now restrictions on the types of topologies that can be used to provide extend UAV service and communications and control.

Networks have the ability to test information flow, processing speed, and rate of data transfer. When those same abilities are considered for UAVs acting in a swarm, the potential exists for swarm UAVs to test signal strength to determine the best path of communication through the network, report their locations, and self-organize, extending communications through a network. The LOS and BLOS limitations mentioned in previous chapters required hub-and-spoke operations to facilitate extended UAV operational range. Using the physical topologies as a guide, instead of a ground team, replace that team with another UAV that can pass on GCS controls, communications, in a semi-autonomous mode, or pass on GPS, and mission conformation and pattern generation information in an autonomous mode.

D. BOTTOM LINE

Technological advances and research are pushing the application of unmanned vehicles in exciting directions. This thesis emphasis is on cost estimation for a new UAV with swarm applications. The new swarm UAV theoretical can be designed to emulate current UAS mission, and expand upon the communication relay mission. Small UAS have a line of sight capability limitation that leaves room for improvement by capitalizing on future technology. The UAVs organic to the Marine Corps (USMC) are the primary focus for this analysis because organic USMC UAVs are habitually small UAVs. The analysis determined a rough cost estimation range for a future AV with new technology.

Chapter II presents research to support the validity of swarm technology and communications through a network of UAVs. Chapter III outlines the analogist and parametric models used during the rough cost estimation. The analysis conducted suggests that a swarm UAV is comparable in cost to legacy UAVs currently in service in the USMC.

The Center for New American Security put several recommendations to the DOD and its services regarding swarm technology:

- Recommendation to the Office of the Secretary of Defense by Paul Scharre; "undertake a study on swarming platforms to examine the potential for low-cost uninhabited systems to impose costs on adversaries" (2014, p 8).

- Second recommendation to the DOA and USMC by Paul Scharre; "Conduct a series of experiments on swarming uninhabited air vehicles for persistent surveillance, close air support, aerial resupply and communications relay to support ground maneuver forces" (2014, p 9).

This thesis took a step forward in answering the recommendations from the Center for New American Security. To answer the first question Chapter VI, analysis suggests that the rough cost estimate based on the data collected and the independent variables used is between $89 million and $0.33 million dollars for a single AV.

To answer the second question this thesis presented the following information. Based on the adaptation of networking topologies in Chapter IV and the research and information presented from scholars and government agencies in Chapter II and V the communication relay mission is a feasible capability to peruse in future swarm UAVs.

E. RECOMMENDATIONS

Future study is required to narrow down the price range for a swarm AV, additionally the analysis should apply more performance and physical variables to establish the price. Weight, price, and capability are a prime concern for the design of future swarm AVs, current UAS in the DOD inventory that were in this thesis characterized as small UAVs should be used to evaluate the value that can be added to the fleet of small UAVs. Future swarm AVs should add to the capabilities mentioned in this thesis and not detract from the capabilities and flexibility of the UAVs characterized as small UAVs in this thesis.

APPENDIX. ADDITIONAL UAV SOURCE MATERIAL

DRAGON EYE

Dragon Eye, the choice of the U.S. Marine Corps, is a fully autonomous, back-packable, bungee-launched small UAS designed to provide "over-the-next-hill" tactical reconnaissance and surveillance information.

With a wingspan of 3.75 feet and a weight of 5.9 pounds, the Dragon Eye provides aerial observation at line-of-sight ranges up to 5 kilometers. Using GPS navigation, the Dragon Eye autonomously flies a route of operator-programmable waypoints. The Dragon Eye's electric motors provide an extremely low noise signature, and the small wingspan makes it difficult to detect in flight.

Dragon Eye's payloads are capable of real-time, high-resolution color or infrared imaging. In addition to viewing imagery in real time, this small UAS enables the operator to "click" capture and store still images on the mission-programming computer.

Mission Descriptions	USMC Light Infantry, Dismounted Urban Warfare
Features	Fully Autonomous Operation, In-Flight Reprogramming, Small Size, Lightweight, Bungee-Launched, Waypoint Navigation, Laptop Mapping, Image Capture.
Payloads	Dual Forward- and Side-Look EO Camera Nose, Forward- and Side-Look Low Light Camera Nose and Side-Look IR Camera Nose.
Endurance	45–60 minutes (Single Use Battery)
Range	5 km
Speed	35 km/h
Operating Altitude (Typ.)	100–500 ft AGL
Span	3.75 ft (1.1 m)
Length	3 ft (0.9 m)
Weight	5.9 lb (2.7 kg)
Launch Method	Bungee-Launched
Recovery Method	Conventional Horizontal Landing

Figure 26. Dragon Eye Overview (from AeroVironment, 2014)

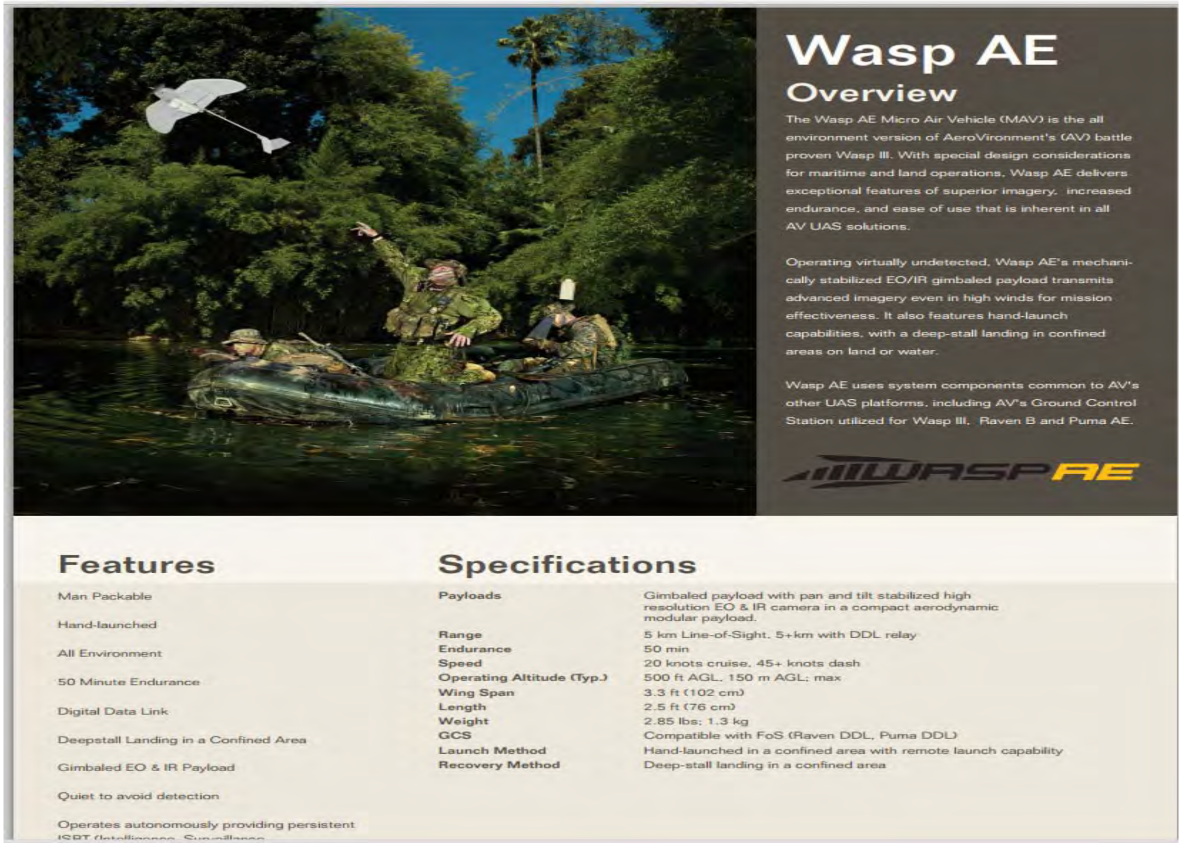


Figure 27. Wasp AE Overview (from AeroVironment, 2014)

PUMA™ AE

INTRODUCING NEW CAPABILITIES

- Longer Endurance
- More Powerful Propulsion
- Extended Mission Flexibility

Overview

Puma AE (All Environment) is a fully waterproof, small, unmanned aircraft system (UAS) designed for land and maritime operations. Capable of landing in water or on land, the Puma AE empowers the operator with an operational flexibility never before available in the small UAS class.

The Puma AE delivers 3.5+ hours of flight endurance with versatile smart batteries options to support diverse mission requirements. Its powerful propulsion system and aerodynamic design make it efficient and easy to launch especially in high altitudes and hotter climates. Puma AE carries a gimbaled payload with an electro-optical (EO) and infrared (IR) cameras. For increased payload capacity, an optional under wing Transit Bay is available, plus a plug and play secondary power adapter is incorporated for increased mission flexibility.

The enhanced precision navigation system with secondary GPS provides greater positional accuracy and reliability of the Puma AE. AV's common ground control system allows the operator to control the aircraft manually or program it for GPS-based autonomous navigation.

Key Features

– All Environment - Fully Waterproof
– 3.5+ Hour Flight Endurance
– Smart Battery options to support diverse missions
– Gimbaled EO & IR Payload
– Increased Payload Capacity with optional under wing Transit Bay
– Powerful and Efficient Propulsion System
– Precision Navigation System with Secondary GPS
– Plug and Play Secondary Power Adapter
– Reinforced Fuselage for Improved Durability

Specifications

Payloads	Gimbaled payload, 360 degree continuous pan, +10 to -90 degrees tilt, stabilized EO, IR camera, and IR Illuminator all in one modular payload.
Range	15 km
Endurance	3.5+ hours
Speed	37-83 km/h, 20 to 45 knots
Operating Altitude (Typ.)	500 ft (152 m) AGL
Wing Span	9.2 ft (2.8 m)
Length	4.6 ft (1.4 m)
Weight	13.5 lbs (6.1 kg)
GCS	Common GCS with Raven, Wasp and Shrike
Launch Method	Hand-launched, rail launch (optional)
Recovery Method	Autonomous or manual deep-stall landing

Figure 28. Puma AE Overview (from AeroVironment, 2014)

Figure 29. Raven Overview (from AeroVironment, 2014)

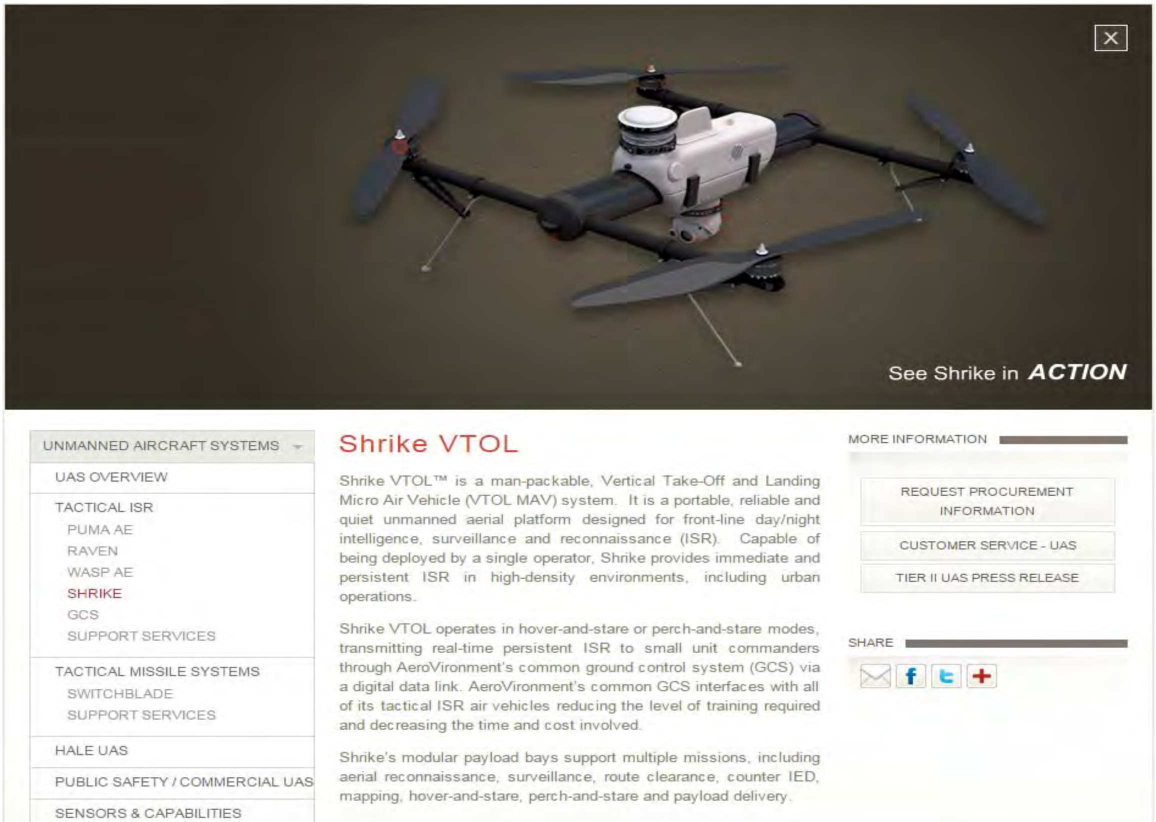


Figure 30. Shrike VTOL Overview (from AeroVironment, 2014)

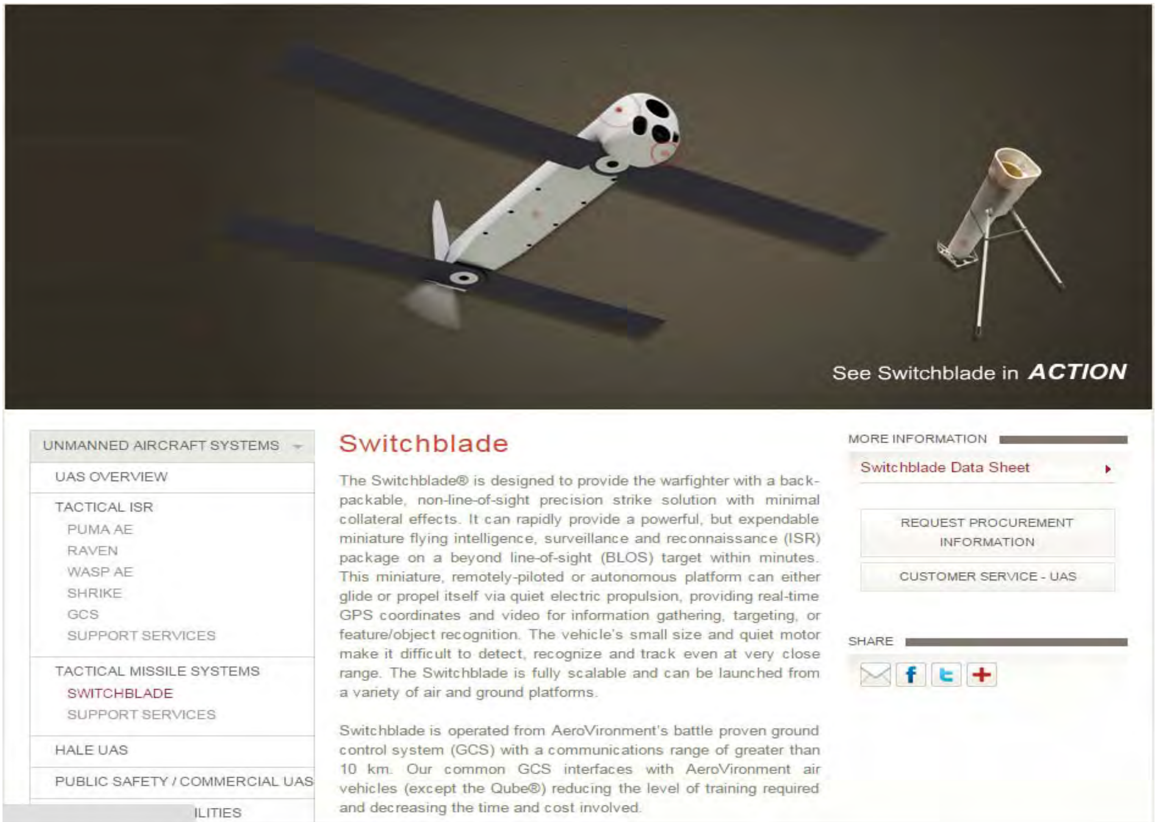
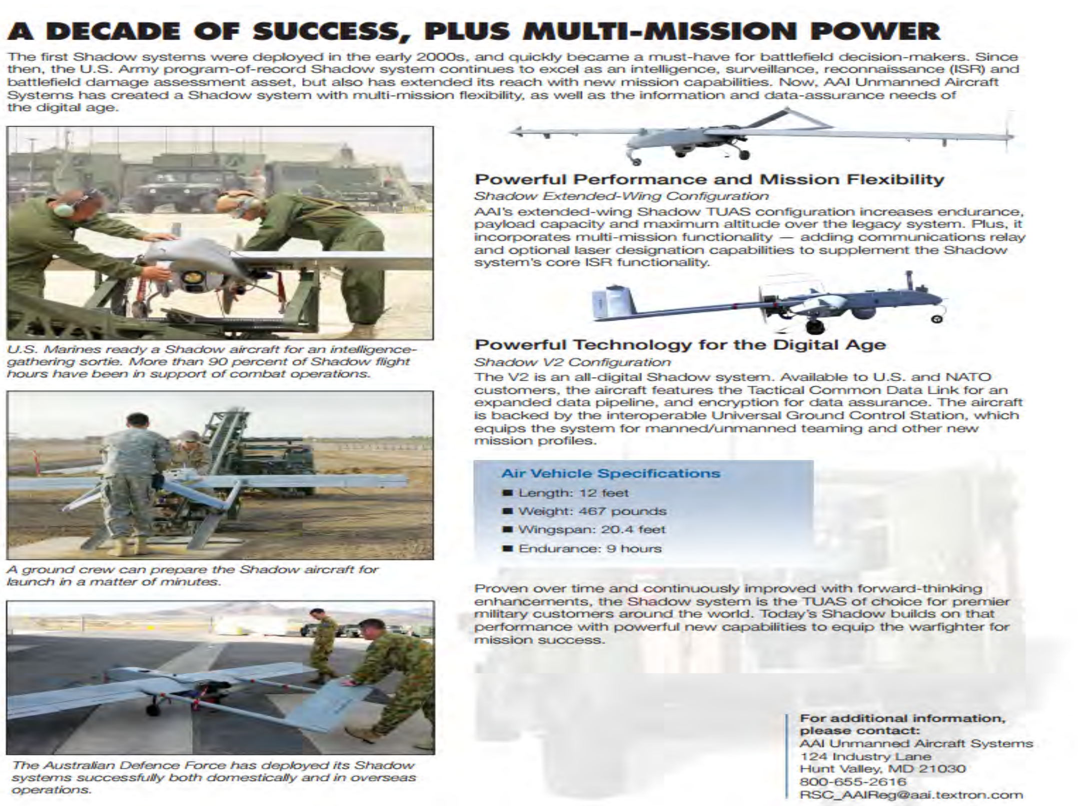


Figure 31. Switchblade Overview (from AeroVironment, 2014)



A DECADE OF SUCCESS, PLUS MULTI-MISSION POWER

The first Shadow systems were deployed in the early 2000s, and quickly became a must-have for battlefield decision-makers. Since then, the U.S. Army program-of-record Shadow system continues to excel as an intelligence, surveillance, reconnaissance (ISR) and battlefield damage assessment asset, but also has extended its reach with new mission capabilities. Now, AAI Unmanned Aircraft Systems has created a Shadow system with multi-mission flexibility, as well as the information and data-assurance needs of the digital age.

U.S. Marines ready a Shadow aircraft for an intelligence-gathering sortie. More than 90 percent of Shadow flight hours have been in support of combat operations.

A ground crew can prepare the Shadow aircraft for launch in a matter of minutes.

The Australian Defence Force has deployed its Shadow systems successfully both domestically and in overseas operations.

Powerful Performance and Mission Flexibility

Shadow Extended-Wing Configuration

AAI's extended-wing Shadow TUAS configuration increases endurance, payload capacity and maximum altitude over the legacy system. Plus, it incorporates multi-mission functionality — adding communications relay and optional laser designation capabilities to supplement the Shadow system's core ISR functionality.

Powerful Technology for the Digital Age

Shadow V2 Configuration

The V2 is an all-digital Shadow system. Available to U.S. and NATO customers, the aircraft features the Tactical Common Data Link for an expanded data pipeline, and encryption for data assurance. The aircraft is backed by the interoperable Universal Ground Control Station, which equips the system for manned/unmanned teaming and other new mission profiles.

Air Vehicle Specifications

- Length: 12 feet
- Weight: 467 pounds
- Wingspan: 20.4 feet
- Endurance: 9 hours

Proven over time and continuously improved with forward-thinking enhancements, the Shadow system is the TUAS of choice for premier military customers around the world. Today's Shadow builds on that performance with powerful new capabilities to equip the warfighter for mission success.

For additional information, please contact:
AAI Unmanned Aircraft Systems
124 Industry Lane
Hunt Valley, MD 21030
800-655-2616
RSC_AAIReg@aai.textron.com

Figure 32. RQ-7 Shadow Overview (from AAI Corporation, 2013)

rotor pitch control via a mechanical servo flap positioned along each of the four rotor blades. Servo flap control eliminates the need for a complex, redundant, high-pressure hydraulic system.

Safer by design **—** No tail rotor and minimal downwash mean safer ground and flight operations.

Low noise **—** No tail rotor yields a low noise signature collectively that will give the K-MAX UAS and the warfighter a tactical advantage during cargo delivery.

Low maintenance **—** Without need for high-maintenance hydraulics or tail rotor, the K-MAX UAS requires minimal daily maintenance and needs no special facilities for maintenance work.

Low operating costs **—** The K-MAX UAS uses an average of 85 gallons of fuel per hour delivering the most efficient lift-to-fuel ratio of any helicopter in its class.

Cargo hook/trolley **—** The K-MAX UAS is built around its cargo hook attached to a curved trolley system. This configuration allows the hook to track across the belly of the airframe, enhancing aircraft maneuverability and load stability.

Four-hook carousel **—** The carousel features four hooks, each activated independently. The ground controller can pre-program the UAS to release a load at four separate destinations during a single flight.

Logistics Support

The Lockheed Martin-led team ensures high availability of the K-MAX UAS to the warfighter.

The team will bring to bear Kaman's logistics support experience established across 250,000+ worldwide flight hours serving the commercial K-MAX fleet.

During the past three years, Kaman has met a 99 percent First Time Fill Rate for parts.

Lockheed Martin brings to the team exceptional supply chain management and global sustainment expertise.

Weights and Measurements		
Max gross weight (with external load)	12,000 lb	5,443 kg
Max take-off weight	7,000 lb	3,175 kg
Empty weight	5,145 lb	2,334 kg
Useful load	6,855 lb	3,109 kg
Cargo hook capacity	6,000 lb	2,722 kg
Lift Performance — ISA +15°C (59°F)		
Sea Level	6,000 lb	2,722 kg
5,000 feet	5,663 lb	2,574 kg
10,000 feet	5,163 lb	2,347 kg
15,000 feet	4,313 lb	1,960 kg
Hover Performance — 4,000 feet, 35°C (95°F)		
Hover IGE	12,000 lb	5,443 kg
Hover OGE	11,500 lb	5,216 kg
Powerplant		
Model - Honeywell T53-17 gas turbine		
Thermodynamic rating		1,800 shaft horsepower
Maximum Airspeed		
Without external load	100 kt	185.2 kph
With external load	80 kt	148.2 kph
Fuel System		
Total usable fuel	219.5 gal	831 liters
Avg fuel consumption	85 gal/hr	321.7 l/hr
Jet A fuel	557.6 lb/hr	252.9 kg/hr
Maximum endurance		12+ hr
Maximum range		1,852km (est)
Maximum speed with external load		148.2km/h
Maximum speed without external load		185.2km/h
Internal fuel endurance		2 hr 41 min
Range with external load		396.3km
Range without external load		494.5km
Approved fuels		Jet A/A-1, JP-5 Jet B/JP-4 JP-8

Figure 33. K-MAX, Cargo UAV Overview (from Lockheed Martin, 2010)

RQ-21A Blackjack

Small Tactical Unmanned Aircraft System (STUAS)

Insitu was awarded the STUAS contract in 2010 to begin development of RQ-21A Blackjack. This program of record for the United States Navy and United States Marine Corps is the first organic and dedicated multi-intelligence Unmanned Aircraft System (UAS) for USMC and USN tactical commanders. The system is modular, flexible and multi-mission capable, providing roll-on, roll-off transitions between land and maritime environments. RQ-21A Blackjack's open architecture payload bays can be customized with imagers, communication capabilities and other tools to deliver exceptional situational awareness.

Key Features

› Rapidly integrates new payloads for expanded mission sets.
› Roll-on, roll-off capability supports ship-to-objective maneuvers.
› Expeditionary and runway independent to support tactical missions on land and at sea.
› Long endurance.
› Minimal footprint accommodates small sites and deck operations.

Dimensions

Length: 8.2 ft / 2.5 m
Wingspan: 16 ft / 4.8 m

Weights

Empty structure weight: 81 lb / 36 kg › Max takeoff weight: 135 lb / 61 kg
Max payload weight*: 39 lb / 17 kg

Performance

Endurance: up to 16 hours
Ceiling: >19,500
Max horizontal speed: 90+ knots
Cruise speed: 60 knots
Engine: 8 HP reciprocating engine with EFI; JP-5, JP-8

Payload Integration

› Onboard power: 350 W for payload
› Onboard connectivity: Ethernet (TCP/IP), data encryption

Standard Payload Configuration

› Electro-optic imager
› Mid-wave infrared imager
› Laser rangefinder
› IR marker
› Communications relay and AIS

Figure 34. RQ-21A Blackjack Overview (from INSITU, 2014)

MQ-1 PREDATOR

Persistent ISR and Strike Aircraft

OBJECTIVE

Perform over-the-horizon long-endurance, medium-altitude Intelligence, Surveillance and Reconnaissance (ISR) and weapons delivery.

CHARACTERISTICS

Wing Span:	55 ft (17m)
Length:	27 ft (8m)
Powerplant:	Heavily Modified Rotax 914 Turbo
Max Gross Takeoff Weight:	2,550 lb (1157 kg)
Fuel Capacity:	625 lb (284 kg)
Payload Capacity:	450 lb int. (204 kg)
	300 lb ext. (136 kg)
Power:	4.8 kW (redundant)

PERFORMANCE

Max Altitude:	25,000 ft
Max Endurance:	40 hr
Max Air Speed:	120 KTAS

CONTROL/DATA LINKS

Line-of-Sight:	C-Band
Over-the-Horizon:	Ku-Band SATCOM

FEATURES

- Solid-state digital avionics
- Remotely piloted or fully autonomous
- MTS-A EO/IR
- Lynx Multi-mode Radar
- SIGINT/ESM system
- GPS and INS
- UHF/VHF voice
- Communications relay
- Hellfire missiles, Griffin missiles

Figure 35. MQ-1 Predator Overview (from General Atomics Aeronautical, 2014)

MQ-9 REAPER/PREDATOR® B

Persistent Multi-mission ISR and Strike Aircraft

OBJECTIVE

Perform multi-mission Intelligence, Surveillance, Reconnaissance (ISR) and "Hunter-Killer" missions over land or sea.

CHARACTERISTICS

Wing Span:	66 ft (20m)
Length:	36 ft (11m)
Powerplant:	Honeywell TPE 331-10
Max Gross Takeoff Weight:	10,500 lb (4763 kg)
Fuel Capacity:	3,900 lb (1769 kg)
Payload Capacity:	850 lb int. (386 kg) 3,000 lb ext. (1361 kg)
Weapons:	Hellfire missiles GBU-12 laser-guided bombs GBU-38 JDAM GBU-49 laser-JDAM
Payloads:	MTS-B EO/IR Lynx* Multi-mode Radar Multi-mode maritime radar Automated Identification System (AIS) SIGINT/ESM system Communications relay
Power:	11.0 kW/45.0 kVA (Block5) (redundant)

FEATURES

- Triple-redundant flight control system
- Redundant flight control surfaces
- Remotely piloted or fully autonomous
- MIL-STD-1760 Stores Management System
- Seven external stations for carriage of payloads
- C-Band line-of-sight data link control
- Ku-Band beyond line-of-sight/SATCOM data link control
- Over 90% system operational availability
- C-130 transportable (or self-deploys)

PERFORMANCE

Max Altitude:	50,000 ft
Max Endurance:	27 hr
Max Air Speed:	240 KTAS

Figure 36. MQ-9 Reaper/Predator B Overview (from General Atomics Aeronautical, 2014)

Global Hawk

Global Hawk

A combat-proven HALE UAS with extraordinary ISR capabilities, providing near-real-time high resolution imagery of large geographical areas all day and night in all types of weather. The Air Force Global Hawk evolved from DARPA technology and was deployed overseas shortly after the September 11, 2001 terrorist attacks. Today, the active Global Hawk enterprise is made up of three complimentary systems. The Global Hawk Comms Gateway was unveiled in 2006 and operates the Battlefield Airborne Communications Node (BACN), a communications system that receives, bridges, and distributes information among all participants in a battle. The Global Hawk Multi-INT is important for situation awareness and intelligence across huge areas of land and carries the sensor systems EISS (Enhanced Integrated Sensor Suite) and ASIP (Airborne Signals Intelligence Payload). The Global Hawk Wide Area Surveillance carries the **Multi-Platform Radar Technology Insertion Program (MP-RTIP)**, which provides game-changing situational awareness and targeting information on both fixed and moving targets. The original Global Hawk model is now flown on scientific research missions by NASA.

Background:

Global Hawk has its origins in the 1995 High-Altitude Endurance Unmanned Aerial Vehicle Advanced Concept Technology Demonstration (HAE UAV ACTD) program initiated by the Defense Advanced Research Projects Agency (DARPA) and the Defense Airborne Reconnaissance Office (DARO). The Global Hawk effort succeeded because it focused on the design and construction of a practical air vehicle that was developmentally mature enough to be transitioned into an operational weapons system. While still a developmental system, the Global Hawk system began supporting overseas contingency operations only two months after the September 11, 2001 attacks. The system has surpassed 125,000 flight hours and midway through 2014 had 100,000 combat/operational flight hours.

Distinctions:

World Records

- April 23, 2001: Global Hawk became the first unmanned, powered aircraft to cross the world's largest ocean when it landed in Australia at 8:40 p.m. local time after a 23-hour, 20-minute trip across the Pacific Ocean.
- March 29, 2013: Global Hawk set the endurance record for a full-scale, operational unmanned aircraft when it completed a 34.3 hour flight at altitudes up to 60,000 feet based out of Grand Forks Air Force Base in North Dakota. The pilots and crew were all women, which all set a record for the longest all-female Global Hawk flight.

Awards

- Dr. James G. Roche Sustainment Excellence Award: The Global Hawk program received this prestigious award from the U.S. Air Force for demonstrating the most improved performance in aircraft maintenance and logistics readiness in fiscal years 2012 and 2013. Global Hawk showed significant improvements in aircraft availability, mission capability and total non-mission capability for maintenance and supply.
- U.S. Air Force Safety Record: Global Hawk has been designated as the platform with the best safety record in the U.S. Air Force in 2013.
- Robert J. Collier Trophy: In 2000, Northrop Grumman along with key government and industry partners received this coveted trophy for designing, building, testing, and operating Global Hawk.
- Airworthiness Certification: Global Hawk is the first UAS to achieve a military airworthiness certification, which along with the certificate of authorization from the Federal Aviation Administration, recognizes Global Hawk's ability to routinely fly within national airspace.

Specifications (Multi-INT and Wide Area Surveillance models)

Wingspan: 130.9 ft (39.9 m)
Length: 47.6 ft (14.5m)
Height: 15.4 ft (4.7 m)
Gross Take-off Weight: 32,250 lbs. (14,628 kg)
Maximum Altitude: 60,000 ft (18.3 km)
Payload : 3,000 lbs (1,360 kg)
Ferry Range: 12,300 nm (22,780 km)
Loiter Velocity: 310 knots True Air Speed (TAS)
On-station Endurance at 1,200 nm: 24 hrs
Maximum Endurance: 32+hrs

Figure 37. Global Hawk Overview (from Northrop Grumman, 2014)

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